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TECHNICAL REPORT 4590

SHOCK-SHOCK INTERACTION STUDIES FOR WEAK INCIDENT SHOCKS

H. E. HUDGINS, JR.
AND
E. M. FRIEDMAN

DECEMBER 1973

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PICATINNY ARSENAL
DOVER, NEW JERSEY

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by

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ABSTRACT

The shock-shock interaction problem for weak incident waves impinging on a supersonic cone has been examined. The purpose of this study was to establish methods for predicting surface pressures since existing methods have been found inadequate for practical problems with weak blast waves. It is shown in this study that one-dimensional theory, which works well for strong blast waves, fails when the components normal to the surface of the flight velocity and of the blast particle velocity become comparable. As a consequence, an axisymmentric two-dimensional solution method was developed using a "primary wave" approximation. This approach has been automated in the PRIMUS computer code. The predictions from the code have been checked against experiment and other theory. The comparisons are presented and the agreement is quite good. The code was also used to predict the cone pressures for DNA Sled Test experiments. The results are presented and compared with the experimental results and other theoretical predictions.

This study established that for weak blast waves the maximum pressure for regular reflection occurs at the Mach reflection limit, not at side-on intercept. The question of whether reflection pressures are even higher on the Mach reflection side of the boundary was examined, but existing prediction methods could not resolve this point. To answer this question, a two-dimensional finite-difference code was also developed for shock-interaction. The feasibility of the method was established, but sufficient calculations have not been conducted at this time to report. It is clear that this finite-difference code could resolve the question definitively upon full development.

CONCLUSIONS

1. The results from "primary wave" analytical approaches developed for both one and two-dimensional problems compare well with exact methods and with experiment within the regular reflection regime.

2. One-dimensional methods have proven insufficient for side-on intercept of conical bodies by weak incident waves at supersonic vehicle velocities.

3. The two-dimensional analytical method has been proven by comparison with experiment to give good estimates of reflection pressures on cones in the regular reflection regime. This method has been automated as the PRIMUS (PRimary Interaction Method for Understanding Shocks) computer program.

4. Regular reflection computations indicate a rapid rise in pressure as the Mach reflection limit is approached, reaching pressures that are about 10% higher than in the side-on situation. These few computations suggest that hypersonic similarity parameter correlation of pressure is still valid for side-on intercept in the weak blast case but that the correlation loses accuracy near the regular reflection pressure maximum which occurs at the regular-Mach reflection boundary.

5. Previously available analytical and numerical estimates of oblique Mach reflection are contradictory and insufficient to settle the question: is there a maximum in shock-shock induced pressure in the Mach reflection regime just before the transition to regular reflection.

6. A two-dimensional finite-difference method using the frozen cells technique has been demonstrated to be feasible. Additional effort and computer time is needed however to produce useful computations in both the Mach and regular reflection regimes to settle the above question.

RECOMMENDATIONS

It is recommended that:

1. the PRIMUS computer program, that was developed, be used for making shock-shock estimates for cones and wedges in the regular reflection regime,

2. an effort should be made to complete the two-dimensional finite-difference method since this seems to be the only computational method capable of settling, once and for all, the question of the magnitude of oblique Mach reflection pressures, .

3. should the completed two-dimensional finite-difference code demonstrate that the Mach reflection regime pressure peak is not the maximum, it should be used to check the PRIMUS code in the regular reflection regime,

4. if this check of the PRIMUS code indicates that it needs to be refined for a more exact calculation of the complete pressure-time history, an effort to make these refinements should be undertaken since PRIMUS requires 1/1000 (or less) of the computer time required by the finite-difference method in the regular reflection regime,

5. improvement of these prediction methods be made before or, at worst, in parallel with further experimental efforts in the shock-shock area.

INTRODUCTION

Shock-shock interaction is the phrase used to refer to the events initiated when the bow wave of a supersonic vehicle encounters an incident wave from an external source, such as a blast wave. It has been known since the early 1960's that such an interaction may result in a transient pressure rise on the vehicle just inside the incident wave front.

The concern of vehicle designers about the effect of this rapid loading and unloading was originally directed toward basic structural integrity. Thus, the mid-60's saw a number of development efforts intended to produce analytical and/or experimental evaluation of shock-shock loading for strong blast waves and hypersonic vehicle velocities. Picatinny Arsenal was actively involved under both DASA, DNA, and AMC sponsorship and produced analytical studies and computer codes in the shock-shock problem area, (Refs 1 to 5).

In order to meet designer's needs, the SLAN computer code was also developed at Picatinny (Ref 6). This code is not an analytical method but utilizes curve fits to the analytical results developed at Picatinny and elsewhere. Its purpose was to estimate shock-shock interaction loading at a blunt body stagnation point and for oblique regular and Mach reflection on cones while requiring a minimum of input and using a mimimum of computer time.

In order to cover the wide range of intercept angles and vehicle geometries cited above, a great many assumptions had to be made and hypotheses accepted without adequate verification. This was clearly stated and experimental confirmation called for in the SLAN report. The development of a facility capable of obtaining the required experimental data had been initiated at Picatinny Arsenal. The feasibility study had been completed and a pilot facility was being tested for performance, (Ref 7), when all work on shock-shock interaction was stopped because there did not appear to be any structural damage problem.

Shock-shock interaction loading reappeared as a problem in a different area of vehicle damage in 1972. This time, the concern was with weak incident waves and lower flight Mach numbers. These conditions invalidated many of the assumptions of the SLAN code - warning messages to this effect are printed as part of its output. They also placed analytically based numerical approaches such as the PASS code (Ref 2) in regimes where the numerics did not converge. Some outside user's still persisted in using the SLAN code and in disseminating the results without including the warnings issued by the code itself (for an example, see Ref 8). This resulted in a decision to see what one and two-dimensional analyses could be quickly performed in order to produce valid answers in the weak wave regime now of interest. The results of this effort are presented in this report.

DISCUSSION

One-Dimensional Methods

The numerical difficulties encountered by the PASS code for weak incident shocks required that a different analytical/numerical approach for incident shock with less than a 4 to 1 pressure ratio be utilized. At the same time, it appeared desirable to use as much already available technology as possible.

Picatinny Arsenal had available a transonic unsteady finite-difference axisymmetric flow field computer program (Ref 9). Part of this code consisted of a subroutine to compute which types of wave forms will evolve from the juxtaposition of two states of a gas. Its analytical basis is taken directly from the analysis beginning on page 362 of Landau and Lifshitz (Ref 10) except that it has been specialized to the same gas on both sides. Other subroutines taken from the transonic program are used to interate to the solution which matches the analytical jump conditions (Rankine-Hugoniot equations) across both waves and meets the required equality of pressure and velocity across the contact surface separating them.

The analytical simplifications made for the computation of shock-shock interaction in the weak wave case were that:

1. the gas is ideal,

2. the continuously varying vehicle flow field properties between the bow shock and the surface are replaced by a number of discontinuous steps with the properties evaluated as the average of the end point values of each strip across the shock layer; the exceptions being that the correct values are used at the shock and at the surface (see Fig 1),

3. when computing the interaction at each node only the primary wave transmitted toward the body is followed from node to node, secondary interactions and waves are ignored.

The heart of the method used lies in the second and third simplifications above. This means that the method used is essentially the method of Moeckel (Ref 11) extended to unsteady flow and it is also related to "shock-expansion" methods. The method developed will henceforth be referred to as the "primary wave" method. The bounds on validity imposed by the kinds of simplifications made in the primary wave method can only be determined by comparison with exact solutions or with experiments. The resulting new one-dimensional computer code using this method was given the acronym WISH (Weak Interaction of SHocks).

At the same time, a one-dimensional "shock-tube" unsteady finite-difference code using the linear method of Godunov (Ref 12) was modified to compute the one-dimensional shock interaction with the desired pre-interaction flow field. The usual difficulty with this approach is that the desired flow field does not remain constant in time because it does not satisfy the one-dimensional flow equations. It was found that this change occurred more rapidly than the shock-shock interaction and wall reflection did for the cases of interest. Thus, valid answers required a method of preserving the desired flow field for a sufficiently long time period. The technique developed here was a cell-by-cell "freezing" of the desired flow field imposed near the wall end of the "shock-tube." The criterion used for unfreezing a particular cell was a 1% change in the pressure of the adjacent up-stream cell due to shock-shock interaction.

Both of the above methods were checked by comparing with other computations, an experiment, and with each other. The comparison cases used were:

1. NOL experiment: flight Mach number (M_∞) of 5.16, blast Mach number (M_b) of 4.89, head-on intercept of a sphere, (Ref 4);

2. PASS code result: side-on intercept of a 5° cone, $M_\infty = 10.0$, blast pressure ratio (P_b / P_∞) = 21, ideal air;

3. Analytical: shock of pressure ratio 1.5 propagating into still air and reflecting normally from a fixed wall.

These cases were all computed with the WISH code and with the one-dimensional finite-difference code, which was given the name 1-D. A comparison of results is given below:

Table 1

One-Dimensional Comparison

CASE NO.	1st REFLECTION PRESSURE (psf)				TIME TO 1st WALL REFLECTION (microseconds)		
	Exp/ Theo	PASS	WISH	1-D	PASS	WISH	1-D
1	3,300 (Exp)	3,280	3,300	3,300	54.4	55.3	57.
2	--	42,360	41,940	41,800	9.88	10.0	10.
3	4,733 (Theo)	--	4,730	4,730	--	74.6	75.

All results are seen to be in good agreement with each other for both pressure and time. It would also appear that any limitations due to the neglect of secondary wave interactions and real gas effects in WISH do not manifest themselves for nearly equal

strength shocks, each with a pressure ratio of about 30 to 1, (Case 1) nor for two very different shock strengths of pressure ratios 21 and 5 (Case 2).

The next step was to see if one-dimensional methods could produce usable results for the side-on intercept of cones with weak blast waves and significant non-parallelism of body and body shock. The case selected for analysis was based on the DNA Shock-Shock Test Program utilizing a rocket sled (Ref 8). An 11.2^{o} cone at Mach 5 was intercepted by a blast wave of pressure ratio 1.6 parallel to the bow shock of the cone (16.6^{o} from the horizontal). The reflected pressures predicted are compared below and can be seen to be in good agreement with each other.

Table 2

Sled Test Pressure Comparison

CODE	1st REFLECTED PRESSURE
WISH	148 psia
1-D	143 psia

The questioning of the validity of a one-dimensional analysis in the weak blast conical case basically arises from one point. Any one-dimensional analysis assumes (among other things) that the incident wave, bow shock, and body surface are parallel. The calculations above made the incident shock and the bow shock parallel and let the cone surface become non-parallel. Next the WISH code was used to compute the case where the incident shock and the cone surface were parallel but the bow shock was not. The result was a wall reflection pressure of 95 pounds per square inch. This large difference indicates that one-dimensional analysis is not adequate.

The question then becomes why was a one-dimensional analysis adequate for stronger incident waves (pressure ratios of 5 to 201) and thin vehicle shock layers (Ref4)? The answer seems to lie in the relative values of the blast particle velocity and the component of cone flight velocity normal to the blast front and, hence, in momentum and energy. When, for example, Check Case #2 and the Sled Test input conditions to the WISH code are compared, the numbers are those given below.

Table 3

SIDE-ON INPUT CONDITIONS COMPARISONS

CASE	CHECK CASE #2	DNA SLED TEST
Vehicle Mach No.	10.0	5.0
Blast Pressure Ratio	21.0	1.6
Blast Particle Velocity	3274 fps	388 fps
Cone Half-Angle	5.0°	11.2°
Cone Shock Angle	7.7°	16.6°
Flight Velocity $\perp$ Bow Shock	1296 fps	1588 fps
Flight Velocity $\perp$ Cone Surface	843 fps	1080 fps

It is clear that the major difference between the cases is that in the strong wave case the blast particle velocity is 70 to 80% of the sum of normal vehicle

velocity and blast particle velocity, while in the weak wave case the proportions are just about reversed and the vehicle velocity component dominates. In the latter situation the choice of whether the blast wave is parallel to the body surface or parallel to the body shock has a substantial effect upon the resulting total velocity in body-fixed coordinates. Conversely, in the strong incident shock case, the total velocity is relatively insensitive to whether the blast is aligned with the body surface or with the body shock since so much of the total velocity is due to the blast particle velocity. It is also clear that the thicker the shock layer, the greater the difference between the component of the flight velocity normal to the body surface and the component normal to the body shock.

As a result the use of one-dimensional analyses for the weak wave case, which is dominated by a two-dimensional flow, is not appropriate.

Two-Dimensional Methods (Planar and Axisymmetric)

It is well established from experiment (Ref 13 to 15) that the initial interaction between a conical shock and an incident wave can be treated as a planar two-dimensional problem. This interaction can be solved exactly by the SWIVEL code available at Picatinny Arsenal. The SWIVEL code is also capable of computing the regular reflection pressure and duration of the transient due to the transmitted incident wave when the wave propagates through a constant property layer after the shock-shock interaction, i.e., the case of a wedge, (See Fig 2 for the basic wave diagram and designation of regions).

The non-uniform shock layer of a cone was treated by the same basic method of using a step-wise approximation of a non-uniform shock layer with which the transmitted incident wave interacts and ignoring the secondary interactions. The SWIVEL code's analytical basis is the computation of the 4-shock intersection that can result when 2 co-planar waves interact. Thus in the new analysis, the isentropic compression between shock and surface

on a cone was modeled by a series of weak shock compressions since, as is well known, weak shocks are very nearly isentropic.

During the development of the new computer code, it was found that a single interior shock compression to the cone surface conditions gave essentially the same reflection pressure as a multi-shock compression. It was also found that for the cone flight conditions of interest, that the entropy jump across a single interior shock was still small enough that the flow was nearly isentropic. Therefore, in the interest of simplicity of coding, getting results sooner, and ease of setting up cases a single shock compression was used. The new computer code was given the acronym PRIMUS (PRimary Interaction Method of Understanding Shocks). PRIMUS also retains the wedge case capability of the SWIVEL code.

Another change that had to be made in SWIVEL to produce PRIMUS was the addition of the ability to compute the quasi-steady conditions on a cone at an angle of attack. The wedge conditions can be, and still are, computed in closed form but the cone conditions at angle of attack can not. Windward ray cone surface pressures at angle of attack are estimated from experimental data collected and correlated by one of the authors in the form of the ratio of actual pressure coefficient to the Newtonian pressure coefficient vs the hypersonic similarity parameter defined by $M_\infty \sin(\theta_c + \alpha)$, where M_∞ is the flight Mach number, θ_c is the cone semi-angle, and α is the angle of attack. Other properties required were taken from Sims' tabulation for cones at small angles of attack (Ref 16) and curve fitted. The curve fits are restricted to the range of parameters currently expected to be required and they have not been checked for accuracy at flight Mach numbers less than 3, or cone half-angles greater than 15°. Furthermore, Sims' angle of attack data is only valid at small angles of attack.

The original SWIVEL code estimated the duration of the pressure transient by assuming that: the reflected

wave was not deflected or altered in strength by its interaction with the contact surface, the expansion wave resulting from the interaction of the reflected wave and the deflected blow wave also propaged back to the body through uniform conditions, and that this expansion was the primary pressure relief mechanism. The duration was defined so that the decay time due to the width of the expansion fan was excluded. This analysis is has not been altered at this time in PRIMUS. Thus, the times predicted for the conical case have been computed using the same basic assumptions. Of course the uniform conditions used are the true cone surface conditions. A desirable future effort would be to incorporate the complete non-uniform layer including interaction with the contact surface.

In parallel with this development, an effort was made to modify a two-dimensional, unsteady finite-difference blunt body flow field program (Ref 17), developed with DNA funding, to compute shock-shock interaction of a plane shock wave with a conical flow field. This approach allows the realistic approximation of two-dimensional effects by allowing for non-parallel body surface, bow shock and blast wave and for the non-uniform shock layer, which is the main flow difference between wedges and cones. This is modeled by the "freezing" of the imposed conical flow just as has been discussed for the one-dimensional finite difference code.

This approach is the only one to date which offers hope for answering certain questions that have been asked in the technical community as to where the maximum wall pressure occurs as a function of intercept angle: is there a maximum on the Mach reflection side of the transition intercept angle from Mach to regular reflection and is it greater than the rise in pressure on the regular reflection side of the transition. The finite difference method is expected to compute both with equal facility. Its one serious drawback would seem to be long running times (about one hour on a CDC 6500 which would make it a candidate for answering certain questions about phenomeonology rather than a code to be used for each case of

interest. The "frozen flow field" used in the one-dimensional finite-difference code and now incorporated into the two-dimensional code does not affect the propagation rate of discontinuities nor reflected pressures. All the unsteady finite-difference methods of lower dimensionality than the real problem do share one difficulty: they compute the final quasi-steady-state solution of the lower-dimensionality problem rather than that of the problem they are being used to approximate. This is not an insuperable problem and it can be resolved by the same non-numerical method used in the PASS code; one estimates the width of the final expansion wave and its strength by simple closed form methods (page 78 of Ref 18) and patches this onto the finite difference solution beginning at the first predicted pressure relief at the body surface.

This study was carried to the point of showing feasibility. The code was modified to planar two-dimensional form, the boundary conditions suitably modified and initial conditions for the shock-shock interaction problem coded and debugged. A true wedge case for regular reflection was set up (as the correct result was known) and the computation begun. The initial interaction of the bow and blast waves proceeded normally and the transmitted blast wave was propagated toward the body surface; then the body surface pressure near the nose began to rise as it should. Unfortunately, at this time development work had to cease. The method appears to be verified as to feasibility and a small effort would determine its accuracy for wedge regular reflection, cone side-on at high Mach number, and Mach reflection for cones or wedges, both head-on and oblique.

Mach Reflection

The question has arisen, provoked by some predictions of Gardner (Ref 20) and two experimental points in Ref 19, as to where the maximum shock-shock interaction surface pressure as a function of intercept angle actually occurs. Gardner at McDonnell-Douglas suggests that it lies at the boundary between Mach and regular reflection on the Mach

reflection side and may exceed any regular reflection pressure. To illustrate this, the results from Ref 20 has been redrawn as Fig 3 of this report.

The experimental pressure ratios in Ref 19 are for a 9° half-angle cone at Mach 3.1 and a blast pressure ratio of 5. The PRIMUS code predicts the result for HARTS Round 7 (40° intercept angle) to within the indicated uncertainty and predicts the limit for regular reflection to be between 39.5° and 39.0°. It is HARTS Round 9, which was supposedly at a 41° angle of intercept, which gave an 80% higher value of reflected pressure. Since the angle of attack of the cone and angle of intercept of the blast are both subject to some uncertainty, this may be evidence for a maximum in pressure just on the Mach reflection side of the limit if the combined effect was to reduce the effective angle of intercept below about 39°. On the other hand, it may be evidence for an error in data acquisition or reduction.

A brief survey of existing analytical work that applies to oblique Mach reflection reveals very little of direct applicability to the cases of interest. Blankenship and Busemann (Ref 21) present some calculations for cones with very small intercept angles (1° or less away from head-on). These results apply to a wave pattern which occurs only at very high vehicle Mach numbers ($M_\infty \gg 10$) for the blast strengths of interest. These calculations can only give an initial slope, which certainly does not remain constant, for the variation with intercept angle while the intercept angles of interest are 20 to 30 degrees. Most fundamentally, the assumed wave pattern does not apply to the flight and blast Mach numbers of current interest.

The wedge analysis and results by Inger (Ref 22) appears, at first glance, to be applicable. His assumption of a weak blast wave is consistent with the current problem and the same method is used for intercept angles from 0° (head-on) to 60°. The assumption of a wedge need

not disqualify this method for useful cone computations, (see the comparison in Fig 4). However, Inger's method also requires a strong bow wave and he appears unwilling to extend his method below a value of the hypersonic similarity parameter of about 2 (see Fig 7 of Ref 22). Upon closer examination, one finds that the restrictions are even more severe. Not only must the hypersonic similarity parameter be large but this must be achieved while keeping the wedge and wedge shock essentially parallel. This implies small wedge angles and high Mach numbers. Thus the range of proposed validity seems to be at too high Mach numbers and for too slender wedges to be of use in the current problem area. Nevertheless, one might hope to at least answer the important question of the <u>trend</u> of peak pressure with intercept angle as it increases from head-on. Inger's method shows a smooth steady increase in peak pressure with increasing obliquity of intercept.

The stated range of validity is that the original wedge shock angle (θ) minus the wedge angle (δ), (all in radians, see also Fig 2) is much less than 1. However, the results seem erroneous, at least for large intercept angles, even in this proposed range of validity. The PRIMUS code computes the <u>exact</u> solutions for shock-shock interactions on wedges which result in regular reflection from the surface. A check case of a 6^{o} wedge at Mach 20 (for which the angular difference is 0.04 radians) with a blast wave of Mach number 1.2 was computed with PRIMUS for intercept angles from 60^{o} to 22^{o}. Results for this case were also computed using the correlations plots in Ref 22. A comparison of reflection pressure/ambient pressure is shown below and plotted in Fig 5.

Table 4

Oblique Intercept Comparison for Wedges

INTERCEPT ANGLE (0° = head-on)	$\left(\frac{P_{refl}}{P_{\infty}}\right)$ Inger	$\left(\frac{P_{refl}}{P_{\infty}}\right)$ PRIMUS (Exact)
10°	12.60	Mach Reflection
20°	13.10	Mach Reflection
25°	13.38	16.11
30°	13.68	15.89
40°	14.41	16.01
50°	15.45	16.24
60°	17.11	16.45

Since the same pre-intercept and quasi-steady pressures were used for both methods for each case, it seems that the difference must be attributed to the value of maximum pressure computed by Inger's method. That method does not predict the minimum in pressure followed by a strong rise with decreasing intercept angle just before the Mach reflection limit that is characteristic of weak incident wave regular reflection. Either Inger's method cannot be applied to as large intercept angles as he believed in 1966 or 0.04 is not $\ll$ 1 for his method at $M_{\infty} = 20$. Since the small pertubation theory used is only valid in the limit as $\delta \rightarrow 0$, this could be the case. Whether or not it is adequate for small intercept angles (Mach reflection) is not well established at this time.

A rather risky extrapolation of cone experimental results in Ref 23 to lower blast strengths and assuming that the hypersonic similarity parameter is a correlating quantity indicates that Inger's results for head-on intercept in this case are in good agreement (see Fig 5). If this is a valid check, and if Inger predicts the correct trend, it indicates that there is no reflection pressure maximum due to Mach reflection. Any rise in pressure near the Mach-regular reflection limit would then be due to the rise which occurs in the regular regime. However, there are too many unconfirmed assumptions to consider the matter settled.

The work of Smyrl (Ref 24) is similar to that of Inger and is applicable to lower flight Mach numbers but it is a linearized analysis which requires that the wedge angle (or wedge angle plus the intercept angle) be small enough that linearization is valid at the desired Mach number. Thus, this method can only give the initial slope of the pressure-intercept angle function for wedges that are intercepted obliquely.

RESULTS

The one-dimensional "primary wave" (WISH code) and finite-difference methods developed (1-D code) were found to be in good agreement with each other and with a number of other exact and experimental results for one-dimensional flow. One-dimensional computations of the DNA Sled Test conditions at a Mach number of 5, an 11.2^{o} half-angle cone with a 16.6^{o} bow wave angle, and a blast pressure ratio of 1.6 indicated that there was a 55% increase in reflected surface pressure in going from a blast wave parallel to the cone surface to a blast wave parallel to the bow shock. Reasons for this difference are detailed in the Discussion and the essential result is that the one-dimensional approximation breaks down at some difference in angle when the three surfaces (blast wave, bow wave, and body) are not parallel. The breakdown occurs at small angles when the vehicle velocity normal to the blast wave dominates the blast particle velocity in the sum of the two terms.

The two-dimensional "primary wave" analytical approximation was automated in a form appropriate for cones in the PRIMUS computer program. Suitable experimental or independent analytical methods to check against are harder to obtain for the oblique intercept of cones. The most suitable predictions available were those by Gardner and Lenertz (MDAC and MMC, respectively, on Fig 2-15 of Ref 8) for the DNA Sled Test. The PRIMUS results are in good agreement with Gardner for pressure and in fair agreement for duration in this case with the blast front nearly parallel to the cone surface. This is shown in Figure 6. Lenertz does not predict durations and the pressure predicted is lower than the other methods. The peak pressure predicted by PRIMUS is 73 to 79 psia, depending on the experimental uncertainty in blast strength and orientation.

The experimental results for the Sled Test are reported in Reference 8. The data in which the most confidence is placed is from the test designated 4B-B3. However, the fact that the high temperature pressure gauges used had too slow a response time and the regular gauges were subjected to a high temperature environment had necessitated a great deal of processing of the raw data. The basic technique was to calibrate the gauges with a shock-tube and use convolution techniques to predict the actual pressures sensed during the rise time of the slower response gauges. Figure 2-15 of Ref 8 shows both the preliminary estimate band and the final estimate of the shock-shock reflection pressure after processing the raw data. The final estimate results in a peak reflected pressure of about 100 psia. This is 32% above the mean estimates of any of the two-dimensional theories including PRIMUS. The final reduced data from the experiment, as taken from Ref 8, are compared with the theoretical predictions on Fig 6. It should be noted however that the gauge in question read the theoetical pre-interaction surface pressure (33 psia) exactly while it read 23% high for the quasi-steady post-interaction pressure. This suggests that the gauge had changed calibration during the shock-shock transient. The PRIMUS predictions and an analytical approximation

from Reference 14 are compared next with a different experiment (Ref 14) which did not depend upon pressure gauges. Since good agreement was achieved with this other experiment, and several theories are in essential agreement for the DNA Sled Test, it would seem that the gauge response problem is the major cause of the disagreement between theory and experiment in that test. Certainly, the experiment was not as definitive as one would have liked. It is understood that a Phase II experiment will be conducted in which it is hoped to eliminate some of the problems mentioned.

The only oblique regular reflection on cones experimental results are those of Ref 14 where pressures are predicted from photographs of shock patterns observed on cone models launched through an oblique shock at 40° from the normal to the cone axis. The incident shock strengths tested are higher than those of interest to the current problem but the cone angles and cone Mach numbers are in the desired range.

The PRIMUS predictions and these experimental results for the ratio of reflected pressure to initial cone pressure are compared in Figures 7 to 10. Only the mean value of the experimental shock wave Mach numbers actually achieved was used at each nominal experimental value for the incident wave strength in the PRIMUS computations. Quite good agreement was found for the variation of the ratio of reflected to initial pressure with shock wave Mach number for both 9° and 15° half-angle cones (see Fig 7 and 8). The PRIMUS predictions of the variation with cone Mach number shows a somewhat stronger dependence on cone Mach number than the experimental data indicates for both 9° and 15° cones, at the higher blast strengths. As the blast strength is reduced, the agreement with experiment becomes better and better and is excellent at the lowest strength tested and should be excellent at the even lower strengths of interest, (see also Fig 9 and 10).

The Two-dimensional theory used in Ref 14 computes the 2-shock interaction exactly but ignores the effect of the non-uniform shock layer on the strength and orientation of the transmitted shock and then computes the reflection at the surface using actual cone surface conditions. The primary wave approach in PRIMUS does consider the non-uniformity of the shock layer. The improvement made by accounting for the change in transmitted wave strength and inclination is discussed below. The predictions of the theory of Ref 14 are always higher than the PRIMUS code predictions. The PRIMUS predictions are clearly in better agreement with experiment for the 9° cones (Fig 9); while in the case of the 15° cones, the data scatter is too great to permit a choice between the two theories (Fig 10). The pressure trends with shock wave Mach number of the two methods can be seen by comparing Fig 7 with 11 and Fig 8 with Fig 12. Again the method used in PRIMUS compares more favorably with experiment for the 9° cones and also appears superior for the 15° cones.

The PRIMUS code achieved this agreement even though various messages-warning of the violation of assumptions-were printed out for some of the required cases. However, these were related to the small angles of attack limit inherent in using Sims' results (Ref 16) for the quasi-steady state or to the duration calculation, which is known to be an approximation. It is hoped that this will not lead to the wholesale neglect of such messages by users as it did with the SLAN code.

The two-dimensional finite difference computer code using a method of "freezing" the imposed preinteraction flow field was brought to the point of proving feasibility of the basic method in two dimensions. The necessity of stopping work prevented checking it against exact solutions for wedges and comparing it with the PRIMUS results for cones. This computer code is the only one which currently has the potential of computing the oblique Mach reflection case and, hence, resolving the uncertainties in this regime dealt with in detail in the Discussion.

In order to permit the ready computation of oblique intercept of cones and wedges in the regular reflection regime, Appendix A of this report contains a brief user's guide to input and output of the PRIMUS code, a listing of PRIMUS, and a wedge and a cone check case.

The PRIMUS code has been used to compute shock-shock results for a cone of semi-angle 11.2° and a blast Mach number of 1.234 at intercept angles from 90° down to the Mach reflection boundary for flight Mach numbers of 3, 5, and 7. The variation of the maximum in surface pressure over ambient pressure with intercept angle and flight Mach number is shown in Fig 13. The maximum reflected pressure ratio at each Mach number is plotted versus flight Mach number on Fig 14. The pressure ratio at an intercept angle of 78.8° (blast wave parallel to cone surface) is also plotted against Mach number on the same figure. This shows that the maximum pressure in the regular reflection regime always occurred at the boundary between Mach and regular reflection, not at the "side-on" conditions, for weak blast waves. At the same blast strength and cone semi-angle, the regular reflection boundary moves to lower intercept angles (more nearly head-on) as the flight Mach number increases. This is due to the stronger bow wave resulting in greater weakening of the transmitted wave. At the same time, however, the reflected pressure over ambient pressure ratio rises with Mach number since the surface pressure rises more strongly with flight Mach number.

The rapid rise in reflection pressure with small changes in intercept angle near the Mach-regular reflection boundary can result in significant errors if the computational angular increment is too large in this region. For example in the above computations at $M_{\infty} = 5$, if calculations are made at one degree intervals, a ratio of reflection pressure to ambient of 6.02 at $\beta = 25^{\circ}$ and Mach reflection at 24° is obtained. But when increments of 0.1° are used the pressure ratio becomes 6.36 at 24.2°, with Mach reflection at 24.1°.

When increments of 0.01° are used, the maximum pressure ratio increases still further to 6.44 at 24.18° with Mach reflection at 24.17° (see also Fig 15).

Earlier side-on results for strong blast waves had correlated well with the hypersonic similarity parameter, (Ref 4). In order to see if this remained true for weak blasts, the Sled Test case and a case at twice the Mach number but the same value of the hypersonic similarity parameter were computed with PRIMUS. The results are compared on Fig 15 for the same blast strength at various intercept angles. The side-on ratios of reflection pressure to ambient are nearly equal, however, the Mach 10 results first undershoot then overshoot the Mach 5 results as the intercept angle decreases. The maximum error, at the same angle, occurs near the Mach reflection limits and is about 10%.

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APPENDIX A

PRIMUS INPUT DESCRIPTION

COLUMN	NAME	FORMAT	EXPLANATION
1-10	M1	F	Flight Mach number
11-20	XIB	F	Blast pressure/ambient pressure[1]
21-30	BETA	F	Blast intercept angle (0^o = head-on)
31-40	DELTA	F	Wedge case = wedge angle; deg. Need not be specified if XI1 is specified. Cone case = flow deflection angle at conical shock, deg. need not be specified if XIS is specified.
41-50	XI1	F	Pressure ratio across wedge shock. Need not be specified if DELTA is specified for wedge. Surface pressure ratio for cone case.
51-60	CONE	F	Cone half-angle, deg. Blank for wedge case
61-70	XIS	F	Cone shock pressure ratio. Need not be specified if DELTA, conical flow deflection angle, is specified. Blank for wedge case.

[1]Analysis currently scaled to ambient pressure = 1, ambient sound speed = 1, ambient density = ratio of specific heats = 1.4.

PRIMUS KEY OUTPUT QUANTITIES[1]

MSUB1	flight Mach number
XISUBB	blast pressure/ambient pressure
BETA	incident wave intercept angle (0° = head-on) deg.
GAMMA	ratio of specific heats (constant)
DELTA	wedge angle, or flow deflection angle at conical shock, deg.
ASUB1	ambient sound speed (scaled to 1)
PSUB1	ambient pressure (scaled to 1)
MSUBB	blast wave Mach number
LAMBDA	final state angle of attack, deg.
THETAF	final state wedge shock angle, deg.
XISUBWF	final state wedge pressure/blast pressure
PSUB3F	final state wedge pressure/ambient pressure
P6/P3F	final state wedge reflection pressure/ambient pressure
PSUBF	cone or wedge reflection pressure/ambient pressure
MSUBF	final state cone surface Mach number
THETAC	final state cone shock angle, windward ray, deg.
ALPHAC	final state cone angle of attack, deg.
CONANGL	cone half angle, deg.

PC/P1 — cone initial surface pressure/ambient pressure

P6/PC — cone reflection pressure/initial cone surface pressure

TAU — cone or wedge dimensionless duration of reflection pressure, ta_1/b, where t is the actual time and b is the axial distance from the wedge or cone tip to the point of interest.[1]

[1]) See also Fig 2 for designation of regions and points.

LISTING OF PRIMUS

```
      PROGRAM PRIMUS (INPUT,TAPE5=INPUT,OUTPUT,TAPE6=OUTPUT)             RENAME    1
C                                                                        RENAME    2
C     PRIMARY INTERACTION METHOD OF UNDERSTANDING SHOCKS                 RENAME    3
C                                                                        RENAME    4
C                                                                        NEGATE    3
C     OBLIQUE BLAST WAVE REFLECTION FROM WEDGE OR CONE IN SUPERSONIC     NEGATE    4
C     FLIGHT WHEN INITIALLY AT ZERO-ANGLE OF ATTACK                      NEGATE    5
C     ANALYSIS RESTRICTED TO REGULAR REFLECTION AND ATTACHED BOW SHOCK   CONE3     1
C     CURRENTLY PREDICTED PRESSURE-TIME HISTORY DOES NOT ALLOW FOR CURV- CONE3     2
C     ATURE OF REFLECTED SHOCK OR ITS INTERACTION WITH THE CONTACT SUR-  CONE3     3
C     FACE                                                               CONE3     4
C     RELEASED FOR PRODUCTION 20 AUGUST 1973 - H. E. HUDGINS             CONE3     5
C                                                                        SWIVEL    5
      REAL M1,MB,M2,LAMBDA,M4P,MU7                                       SWIVEL    6
C     DETACHED WEDGE FINAL SHOCK ERROR RETURN BYPASSED FOR CONE CASE     WEDGEC    1
C     17 OCT 1973                                                        WEDGEC    2
C                                                                        WEDGEC    3
C                                                                        RENAME    5
C     PROGRAM RENAMED PRIMUS, 24 OCT 1973                                RENAME    6
C                                                                        RENAME    7
      REAL M1S                                                           NUCONE    1
C                                                                        SWIVEL    7
      COMMON/APOINT/VA,V1,V2,V3,EPS,ANG1,ANG2,ANG3                       SWIVEL    8
      COMMON/BREG/MB,VBN,ETAB,A2,UB,U2,M2                                SWIVEL    9
      COMMON/CONST/G,GP,GM,CON,A1,P1                                     SWIVEL   10
      COMMON/FREG/LAMBDA,DELTAF,THETAF,XIWF, ETAWF,A3F,P3F,U3F           SWIVEL   11
      COMMON/INPUT/M1,XIB,BETA,DELTA                                     SWIVEL   12
      COMMON/RREG/OMEGAI,DELTAR,V4P,M4P,THETAR,OMEGAR,XIR,P6,P6P3,P6P3F  SWIVEL   13
      COMMON/TDREG/THETAT,THETAD,XIT,XID,ANG4,ANG5,ANGT,ANGD,ETAT,       SWIVEL   14
     CA4A3                                                               SWIVEL   15
      COMMON/TIME/APOR,CPOR,CHI,OCOR,VC,PSI7,U7,V7,MU7,PSIM,EPOR,VE,     SWIVEL   16
     COPOR,TAU                                                           SWIVEL   17
      COMMON/WREG/ THETA,XIW,ETAW,A3,AM3                                 JUMP      1
      COMMON/BSAVE/BM,SVBN,SETAB,SA2,SUB,SU2,SM2,BETAS                   NUCONE    2
C                                                                        SWIVEL   19
 1000 FORMAT(8F10.5)                                                     SWIVEL   20
 1010 FORMAT(1H1,18X,44HOBLIQUE BLAST WAVE REFLECTION FROM WEDGE OR ,    NEGATE    6
     1 23HCONE IN SUPERSONIC FLOW,///)                                   NEGATE    7
 1020 FORMAT(1H ,17HINPUT CONDITIONS-,//,6X,5HMSUB1,6X,6HXISUBB,4X,      SWIVEL   23
     *        9HBETA(DEG),3X,10HDELTA(DEG))                              SWIVEL   24
 1030 FORMAT(1H ,F11.5,9F12.5)                                           SWIVEL   25
 1040 FORMAT(1H0,10HCONSTANTS-,//,6X,5HGAMMA,7X,5HASUB1,7X,5HPSUB1)      SWIVEL   26
 1050 FORMAT(1H0,29HCONDITIONS ACROSS BLAST WAVE-,//,6X,5HMSUBB,7X,      SWIVEL   27
     *        6HVSUBBN,5X,7HETASUBB,6X,5HASUB2,7X,5HUSUBB,7X,5HUSUB2,7X, SWIVEL   28
     *        5HMSUB2)                                                   SWIVEL   29
 1060 FORMAT(1H0,49HNEW STEADY STATE CONDITIONS, (F), ATTACHED FINAL ,   SWIVEL   30
     *        10HBOW SHOCK-,//,38H   LAMBDA(DEG) DELTAF(DEG) THETAF(DEG), SWIVEL  31
     *        3X,7HXISUBWF,5X,8HETASUBWF,5X,6HASUB3F,5X,6HPSUB3F,6X,     SWIVEL   32
     *        6HUSUB3F)                                                  SWIVEL   33
 1070 FORMAT(1H0,49HNEW STEADY STATE CONDITIONS, (F), DETACHED FINAL ,   SWIVEL   34
     C        33HBOW SHOCK, PROGRAM IS TERMINATED-)                      SWIVEL   35
 1080 FORMAT(1H0,48HCONDITIONS ACROSS BOW WAVE, DETACHED BOW SHOCK, ,    SWIVEL   36
     C        19HPROGRAM TERMINATED-)                                    SWIVEL   37
 1090 FORMAT(1H0,47HCONDITIONS ACROSS BOW WAVE, ATTACHED BOW SHOCK-,//,  SWIVEL   38
     1        13H    THETA(DEG),4X,6HXISUBW,6X,7HETASUBW,6X,5HASUB3,8X,5HM JUMP      2
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      2SUB3.)                                                            JUMP       3
 1100 FORMAT(1H0,30HSTEADY CONDITIONS FOR POINT A-,/)                    SWIVEL    40
 1110 FORMAT(1H ,5X,5HVSUBA,7X,5HVSUB1,7X,5HVSUB2,7X,5HVSUB3,5X,         SWIVEL    41
     *        46HEPSA(DEG)  SIGMA1(DEG) SIGMA2(DEG) SIGMA3(DEG))         SWIVEL    42
 1120 FORMAT(1H ,5X,5HVSUBA,7X,5HVSUB1,7X,5HVSUB2,7X,5HVSUB3,5X,         SWIVEL    43
     *        44HEPSB(DEG)  TAU1(DEG)   TAU2(DEG)   TAU3(DEG))           SWIVEL    44
 1130 FORMAT(1H0,44HCONDITIONS IN REGIONS 4 AND 5, NO SOLUTION, ,       SWIVEL    45
     C        19HPROGRAM TERMINATED-)                                    SWIVEL    46
 1140 FORMAT(1H0,30HCONDITIONS IN REGIONS 4 AND 5-,/)                    SWIVEL    47
 1150 FORMAT(1H ,25H  THETAT(DEG) THETAD(DEG),4X,6HXISUBT,6X,6HXISUBD,   SWIVEL    48
     *        48H  SIGMA4(DEG) SIGMA5(DEG)  PHIT(DEG)    PHID(DEG),5X,   SWIVEL    49
     *        7HETASUBT,6X,5HA4/A3)                                      SWIVEL    50
 1160 FORMAT(1H ,25H  THETAT(DEG) THETAD(DEG),4X,6HXISUBT,6X,6HXISUBD,   SWIVEL    51
     *        48H   TAU4(DEG)    TAU5(DEG)   PSIT(DEG)    PSID(DEG),5X,  SWIVEL    52
     *        7HETASUBT,6X,5HA4/A3)                                      SWIVEL    53
 1170 FORMAT(1H0,42HCONDITIONS OF REGULAR REFLECTION, REGULAR ,          SWIVEL    54
     C        46HREFLECTION LIMIT EXCEEDED, PROGRAM TERMINATED-)         SWIVEL    55
 1180 FORMAT(1H0,33HCONDITIONS OF REGULAR REFLECTION-,//                 SWIVEL    56
     *        48H  OMEGAI(DEG) DELTAR(DEG)     VSUB4P       MSUB4P,      SWIVEL    57
     *        46H  THETARP(DEG) OMEGAR(DEG)     XISUBR      PSUB6,8X,    SWIVEL    58
     *        18HP6/P3         P6/P3F)                                   SWIVEL    59
 1190 FORMAT(1H0,47HNOMINAL TIME OF PEAK OVERPRESSURE NOT COMPUTED-)     SWIVEL    60
 1200 FORMAT(1H0,34HNOMINAL TIME OF PEAK OVERPRESSURE-,//,7X,4HAP/R,8X,  SWIVEL    61
     *        4HCP/R,8X,4HOC/R,8X,4HEP/R,8X,4HOP/R)                      SWIVEL    62
 1210 FORMAT(1H0,3X,44HCHI(DEG)    PSI7(DEG)    MU7(DEG)   PSIM(DEG))    SWIVEL    63
 1220 FORMAT(1H0,5X,5HVSUBC,7X,5HUSUB7,7X,5HVSUB7,7X,5HVSUBE,9X,3HTAU)   SWIVEL    64
 1230 FORMAT(1H0,34HNOMINAL TIME OF PEAK OVERPRESSURE-,//,7X,4HAP/R,8X,  SWIVEL    65
     *        4HCP/R,8X,4HOC/R)                                          SWIVEL    66
 1240 FORMAT(1H0,5X,5HVSUBC,7X,5HUSUB7,7X,5HVSUB7,9X,3HTAU)              SWIVEL    67
 1250 FORMAT( //,34X,51HTIMEB HAS FAILED. TIMEA USED TO EXTRAPOLATE IN T SWIVEL    68
     CAU.)                                                               SWIVEL    69
 1260 FORMAT(//,36X,48HSHOCK LAYER GREATER THAN 5 DEG. ERROR INCREASED.) SPACE      1
 1270 FORMAT(1H0,10X,22HESTIMATED RESULTS ARE:,3X,6HTAU = ,G12.5,3X,7HP6 DOPRINT    1
     1P3 = ,G12.5,/)                                                     DOPRINT    2
 1280 FORMAT(//,45X,38HTHIS CASE IS BEING COMPUTED FOR A CONE.)          CONE       1
 1290 FORMAT(//,56X,16HCONE RESULTS ARE.)                                CONE       2
 1300 FORMAT( //,8X,5HMSUBF,7X,6HTHETAC,7X,7HALPHAFC,6X,7HCONANGL,7X,5HP REALP2     1
     1C/PI,8X,5HP6/PC,7X,7H PSUB6 ,5X,6HPSCALE,7X,7HTIMSCALE,7X,3HTAU,/,4 REALP2    2
     2X,10(F10.6,3X),)                                                   REALP2     3
 1400 FORMAT(/,35X,54HSINGLE STEP SHOCK COMPRESSION TO CONE SURFACE PRES JUMP       4
     1SURE.)                                                             JUMP       5
 1410 FORMAT(/,28X,12HPCONE/PSHOCK,5X,6HMSUBIW,3X,12HSHOCK  ANGLE,2X,12H JUMP       6
     1DEFL.  ANGLE,2X,12HENTROPY JUMP,2X,12HBLAST  ANGLE,/28X,7(G12.5,2X JUMP       7
     2),)                                                                JUMP       8
 1420 FORMAT(1H0,2X,46HTIMES MAY BE IN ERROR - COMPUTATION CONTINUES,)   CONE3      6
C                                                                        DOPRINT    3
   10 CONTINUE                                                           INITIAL    1
      M=0                                                                DOPRINT    4
      N=0                                                                TAUB-1     1
      G=1.4                                                              SWIVEL    73
      GINV=1./G                                                          CONEFIX    1
      GP=G+1.                                                            SWIVEL    74
      GM=G-1.                                                            SWIVEL    75
      CON=3.1415927/180.                                                 SWIVEL    76
      PI=1.                                                              SWIVEL    77
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          AI=1.                                                          SWIVEL    78
          PSCALE=1.                                                      JUMP       9
          ASCALE=1.                                                      JUMP      10
          NWALL=0                                                        JUMP      11
          TSCALE=1.                                                      INTERP     1
          NERR=0                                                         CONE3      7
C                                                                        CONE       5
C         IF CONE CASE IS TO BE COMPUTED,DELTA IS FLOW DEFLECTION ANGLE AT CONE     6
C         CONICAL SHOCK,XI1 IS THE CONE SURFACE PRESSURE RATIO, AND CONE IS CONE    7
C         THE CONE HALF-ANGLE. ALL ANGLES INPUT  IN DEGREES.             CONE       8
C         THE PRESSURE RATIO ACROSS  THE CONICAL SHOCK,XIS,MAY BE INPUT  CONE3      8
C         INSTEAD OF THE FLOW DEFLECTION ANGLE,DELTA.                    CONE3      9
C                                                                        CONE       9
          READ 1000,M1,XIB,BETA,DELTA,XI1,CONE,XIS                       CONE3     10
          IF(EOF(5) .NE. 0.) STOP                                        SWIVEL    80
          IF(XIS .NE. 0.) GO TO 21                                       CONE3     11
          IF(DELTA .NE. 0.) GO TO 20                                     SURFP      2
          CALL WEDGE(XI1,M1,DELTA,THETA)                                 SURFP      3
          GO TO 20                                                       CONE3     12
       21 CALL WEDGE(XIS,M1,DELTA,THETA)                                 CONE3     13
       20 IF(M .EQ. 1) GO TO 270                                         NOPRINT    1
          PRINT 1010                                                     NOPRINT    2
          PRINT 1020                                                     SWIVEL    82
          PRINT 1030,M1,XIB,BETA,DELTA                                   SWIVEL    83
          PRINT 1040                                                     SWIVEL    84
          PRINT 1030,G,A1,P1                                             SWIVEL    85
          PRINT 1050                                                     SWIVEL    86
      270 CALL BLSTWV                                                    SWIVEL    87
          IF(M .EQ. 1) GO TO 271                                         NOPRINT    3
          PRINT 1030,MB,VBN,ETAB,A2,UB,U2,M2                             SWIVEL    88
          IF(NWALL .EQ. 1) GO TO 271                                     NUCONE     3
C                                                                        NUCONE     4
C         SAVE INITIAL INTERACTION CONDITIONS FOR BLAST                  NUCONE     5
C                                                                        NUCONE     6
          BM=MB                                                          NUCONE     7
          SVBN=VBN                                                       NUCONE     8
          SETAB=ETAB                                                     NUCONE     9
          SA2=A2                                                         NUCONE    10
          SUB=UB                                                         NUCONE    11
          SU2=U2                                                         NUCONE    12
          SM2=M2                                                         NUCONE    13
          BETAS=BETA                                                     NUCONE    14
      271 CALL FINAL(NERR)                                               NOPRINT    4
          IF(NERR)30,30,40                                               SWIVEL    90
       30 IF(M .EQ. 1) GO TO 50                                          NOPRINT    5
          PRINT 1060                                                     NOPRINT    6
          PRINT 1030,LAMBDA,DELTAF,THETAF,XIWF,ETAWF,A3F,P3F,U3F         SWIVEL    92
          GO TO 50                                                       SWIVEL    93
C                                                                        WEDGEC     4
C         DETACHED SHOCK FOR WEDGE COMPUTATION NEED NOT APPLY IN CONE CASE WEDGEC   5
C                                                                        WEDGEC     6
       40 IF(CONE .NE. 0.) GO TO 30                                      WEDGEC     7
          GO TO 10                                                       SWIVEL    95
       50 CALL BOWAVE(NERR)                                              SWIVEL    96
          IF(NERR) 70,70,60                                              SWIVEL    97
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   60 PRINT 1080                                                        SWIVEL    98
      GO TO 10                                                          SWIVEL    99
   70 IF(M .EQ. 1) GO TO 71                                             NOPRINT    7
      PRINT 1090                                                        NOPRINT    8
      PRINT 1030,THETA,XIW,ETAW,A3,AM3                                  JUMP      12
      PRINT 1100                                                        SWIVEL   102
   71 CALL POINTA(ICASE)                                                NOPRINT    9
      GO TO (80,90),ICASE                                               SWIVEL   104
   80 IF(M .EQ. 1) GO TO 81                                             NOPRINT   10
      PRINT 1110                                                        NOPRINT   11
      GO TO 100                                                         SWIVEL   106
   90 IF(M .EQ. 1) GO TO 81                                             NOPRINT   12
      PRINT 1120                                                        NOPRINT   13
  100 PRINT 1030,VA,VI,V2,V3,EPS,ANG1,ANG2,ANG3                         SWIVEL   108
   81 CALL FORFIV(NERR)                                                 NOPRINT   14
      IF(NERR)120,120,110                                               SWIVEL   110
  110 PRINT 1130                                                        SWIVEL   111
      GO TO 10                                                          SWIVEL   112
  120 CONTINUE                                                          CONEFIX    2
      IF(M .EQ. 1) GO TO 122                                            CONEFIX    3
      PRINT 1140                                                        NOPRINT   16
      GO TO (130,140), ICASE                                            SWIVEL   114
  130 PRINT 1150                                                        SWIVEL   115
      GO TO 150                                                         SWIVEL   116
  140 PRINT 1160                                                        SWIVEL   117
  150 PRINT 1030,THETAT,THETAO,XIT,XID,ANG4,ANG5,ANGT,ANGD,ETAT,A4A3    SWIVEL   118
  122 IF(CONE .EQ. 0.) GO TO 121                                        CONEFIX    4
      IF(M .EQ. 0) PRINT 1280                                           CONEFIX    5
C                                                                       NUCONE    15
C     COMPUTE 1-STEP COMPRESSION TO CONE SURFACE                        NUCONE    16
C                                                                       NUCONE    17
      ALFA=LAMBDA                                                       JUMP      13
      ALSAVE=LAMBDA                                                     JUMP      14
      SAVEM=M2                                                          JUMP      15
      OLSVE=DELTA                                                       INTERP     2
      DELTA=CONE                                                        CONE      14
      XSAVE=XIW                                                         CONE      15
      CSAVE=A3/A1                                                       NUCONE    18
      IF(NWALL.EQ. 1) GO TO 25                                          JUMP      16
      NWALL=1                                                           JUMP      17
      XIW=XI1/XSAVE                                                     JUMP      18
      ETAW=XIW**(-GINV)                                                 JUMP      19
      A3=SQRT(XIW*ETAW)                                                 JUMP      20
      M1S=M1                                                            NUCONE    19
      M1=AM3                                                            JUMP      21
      THETA=ASIN(SQRT((0.5*GP*(XIW-1.)/G)+1.)/M1)                       JUMP      22
      SUMN=(SIN(THETA)*M1)**2                                           JUMP      23
      DELTA=ATAN((2.*(SUMN-1.))/((M1*M1*(G+COS(2.*THETA))+2.)*TAN(THETA) JUMP     24
     1))                                                                JUMP      25
      THETA=THETA/CON                                                   JUMP      26
C                                                                       NUCONE    20
C     SAVE COMPRESSION SHOCK ANGLE                                      NUCONE    21
C                                                                       NUCONE    22
      THOLO=THETA                                                       JUMP      27
      DELTA=DELTA/CON                                                   JUMP      28
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      DELSOR=(GP/(12.*G*G))*(XIW-1.)**3                         JUMP      29
      M1=AM3                                                    JUMP      30
      XIBS=XIB                                                  NUCONE    23
      XIB=XIT                                                   JUMP      31
      PSCALE=XSAVE                                              NUCONE    24
      ASCALE=CSAVE                                              NUCONE    25
      GO TO (500,510), ICASE                                    JUMP      34
  500 BETA=ANGT                                                 JUMP      35
      GO TO 520                                                 JUMP      36
  510 BETA=90.-ANGT                                             JUMP      37
  520 PRINT 1400                                                JUMP      38
      PRINT 1410,XIW,M1,THETA,DELTA,DELSOR,BETA                 JUMP      39
      GO TO 20                                                  JUMP      40
   25 AMF=SAVEM                                                 JUMP      41
      ALFA=ALSAVE                                               JUMP      42
  123 CALL FCONE(CONE,XIBS,MIS)                                 NUCONE    26
      CM=U3F/A3F                                                NEGATE     8
      IF(M .EQ. 1) GO TO 330                                    NEGATE     9
      PRINT 1060                                                NUCONE    28
      PRINT 1030,LAMBDA,DELTAF,THETAF,XIWF,ETAWF,A3F,P3F,U3F    NUCONE    29
C                                                               NUCONE    30
C     CONVERTING FINAL CONE VALUES TO COMPRESSION VALUES        NUCONE    31
C                                                               NUCONE    32
  330 CONTINUE                                                  NEGATE    10
      XIWF=XIWF/PSCALE                                          NUCONE    33
      ETAWF=ETAWF/(PSCALE**(1./G))                              NUCONE    34
      A3F=A3F/ASCALE                                            NUCONE    35
      P3F=P3F/PSCALE                                            NUCONE    36
      U3F=U3F/ASCALE                                            NUCONE    37
      ALFA=LAMBDA                                               NUCONE    38
  121 CALL REGRFL(ICASE,NERR)                                   NOPRINT   17
      IF(NERR)170,170,160                                       SWIVEL   120
  160 PRINT 1170                                                SWIVEL   121
      NERR=9                                                    SWIVEL   122
      GO TO 10                                                  SWIVEL   123
  170 IF(M .EQ. 1) GO TO 171                                    NOPRINT   18
      PRINT 1180                                                NOPRINT   19
      PRINT 1030,OMEGAI,DELTAR,V4P,M4P,THETAR,OMEGAR,XIR,P6,P6P3,P6P3F SPELL 1
  171 GO TO(180,190),ICASE                                      NOPRINT   20
  180 CALL TIMEA(NERR)                                          SWIVEL   127
      IF(NERR .EQ. 1) GO TO 6969                                SWIVEL   128
  181 IF(CONE .EQ. 0.) GO TO 210                                CONE3     14
      IF(M .EQ. 1) GO TO 211                                    INTERP     7
      XIW=XIW*PSCALE                                            JUMP      43
      P6C=XIW*P6P3                                              REALP2     4
      TSCALE=ASCALE                                             JUMP      45
      TAU=TAU*ASCALE                                            JUMP      46
      TAUX=TAUX*ASCALE                                          JUMP      47
      PRINT 1290                                                CONE      25
      PRINT 1300, CM,THETAF,ALFA,DELTA,XIW,P6P3,P6C,PSCALE,TSCALE,TAU REALP2 5
      GO TO 10                                                  CONE      27
  190 CALL TIMEB(NERR)                                          DOPRINT    6
      IF(N .EQ. 4 .AND. NERR .GT. 0) GO TO 440                  TAUB-1     6
      IF(NERR .LE. 0) GO TO 220                                 SWIVEL   131
      M=1                                                       NOPRINT   21
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          PRINT 1250                                              TAUB-1      7
          BI=BETA                                                 DOPRINT     7
          IF(CONE .NE. 0.) THETA=THOLD                            JUMP       48
          IF(THETA-DELTA .GT. 5.) GO TO 250                       TAUB-1      8
      260 BETA=(90.-THETA)*.999                                   TAUB-1      9
          NERR=0                                                  TAUB-1     10
          PA=P6P3                                                 TAUB-1     11
          IF(CONE .EQ. 0.) GO TO 261                              CONEFIX    12
          ASAVE=AMF                                               CONEFIX    13
          THSAVE=THETAS                                           CONEFIX    14
          ALSAVE=ALFA                                             CONEFIX    15
          DSAVE=DELTA                                             CONEFIX    16
          XISAVE=XIW                                              CONEFIX    17
          XTSAVE=XIT                                              CONEFIX    18
          TSAVE=TSCALE                                            CONEFIX    19
          DELTA=DLSVE                                             INTERP      8
      261 CONTINUE                                                CONEFIX    20
          N=2                                                     TAUB-1     12
          B2=BETA                                                 TAUB-1     13
          GO TO 20                                                DOPRINT     8
      200 PRINT 1190                                              SWIVEL    132
          GO TO 10                                                SWIVEL    133
      210 IF(M .EQ. 1) GO TO 211                                  NOPRINT    22
          PRINT 1200                                              NOPRINT    23
          PRINT 1030,APOR,CPOR,OCOR,EPOR,OPOR                     SWIVEL    135
          PRINT 1210                                              SWIVEL    136
          PRINT 1030, CHI,PSI7,MU7,PSIM                           SWIVEL    137
          PRINT 1220                                              SWIVEL    138
          PRINT 1030, VC,U7,V7,VE,TAU                             SWIVEL    139
      211 IF(N .EQ. 2) GO TO 290                                  DOPRINT     9
          IF(N .EQ. 3) GO TO 300                                  DOPRINT    10
          IF(N .EQ. 4) GO TO 420                                  DOPRINT    11
          GO TO 10                                                SWIVEL    140
      220 IF(M .EQ. 1) GO TO 221                                  NOPRINT    24
          IF(CONE .NE. 0.) GO TO 222                              CONE       28
          PRINT 1230                                              NOPRINT    25
          PRINT 1030, APOR,CPOR,OCOR                              SWIVEL    142
          PRINT 1210                                              SWIVEL    143
          PRINT 1030, CHI,PSI7,MU7,PSIM                           SWIVEL    144
          PRINT 1240                                              SWIVEL    145
          PRINT 1030,VC,U7,V7,TAU                                 SWIVEL    146
      221 IF(N .EQ. 4) GO TO 420                                  DOPRINT    12
          GO TO 10                                                SWIVEL    147
      222 CONTINUE                                                INTERP      9
          XIW=XIW*PSCALE                                          JUMP       49
          P6C=XIW*P6P3                                            REALP2      6
          TSCALE=ASCALE                                           JUMP       51
          TAU=TAU*ASCALE                                          JUMP       52
          TAUX=TAUX*ASCALE                                        JUMP       53
          PRINT 1290                                              CONE       30
          PRINT 1300, CM,THETAF,ALFA,DELTA,XIW,P6P3,P6C,PSCALE,TSCALE,TAU  REALP2  7
          GO TO 10                                                CONE       32
      250 IF(THETA-DELTA .GT. 15.) GO TO 200                      TAUB-1     15
          WRITE(6,1260)                                           TAUB-1     16
          GO TO 260                                               TAUB-1     17
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 290 T2=TAU                                                             TAUB-1      18
     NERR=0                                                             TAUB-1      19
     N=3                                                                TAUB-1      20
     BETA=B2-5.                                                         TAUB-1      21
     B3=BETA                                                            TAUB-1      22
     IF(CONE .NE. 0.) THETA=THOLD                                       JUMP        54
     IF(CONE .NE. 0.) DELTA=DLSVE                                       JUMP        55
     GO TO 20                                                           DOPRINT     13
 300 T3=TAU                                                             TAUB-1      24
     NERR=0                                                             TAUB-1      25
     N=4                                                                TAUB-1      26
     BETA=90.                                                           TAUB-1      27
     IF(CONE .NE. 0.) THETA=THOLD                                       JUMP        56
     IF(CONE .NE. 0.) DELTA=DLSVE                                       JUMP        57
     B4=BETA                                                            TAUB-1      28
     GO TO 20                                                           DOPRINT     14
 420 T4=TAU                                                             TAUB-1      30
     BETA=B1                                                            TAUB-1      31
     CALL PARA (T2,T3,T4,B2,B3,B4,CT1,CT2,CT3)                          TAUB-1      32
     TAU=CT1+CT2*BETA+CT3*BETA*BETA                                     TAUB-1      33
     TAU=ABS(TAU)                                                       CONE3       15
     P6P3=PA                                                            TAUB-1      34
     IF(CONE .NE. 0.) GO TO 421                                         CONE        33
     PRINT 1270,TAU,P6P3                                                DOPRINT     15
     GO TO 10                                                           TAUB-1      35
 421 AMF=ASAVE                                                          CONEFIX     21
     THETAS=THSAVE                                                      CONEFIX     22
     ALFA=ALSAVE                                                        CONEFIX     23
     DELTA=DSAVE                                                        CONEFIX     24
     XIW=XISAVE                                                         CONEFIX     25
     XIT=XTSAVE                                                         CONEFIX     26
     XIW=XIW*PSCALE                                                     JUMP        58
     P6C=XIW*P6P3                                                       REALP2       8
     TSCALE=ASCALE                                                      JUMP        60
     TAU=TAU*ASCALE                                                     JUMP        61
     TAUX=TAUX*ASCALE                                                   JUMP        62
     PRINT 1290                                                         CONEFIX     29
     PRINT 1300, CM,THETAF,ALFA,DELTA,XIW,P6P3,P6C,PSCALE,TSCALE,TAU    REALP2       9
     GO TO 10                                                           CONE        36
 440 N=4                                                                TAUB-1      36
     BETA=B3-2.                                                         TAUB-1      37
     IF(CONE .NE. 0.) THETA=THOLD                                       JUMP        63
     IF(CONE .NE. 0.) DELTA=DLSVE                                       JUMP        64
     B4=BETA                                                            TAUB-1      38
     NERR=0                                                             TAUB-1      39
     GO TO 20                                                           DOPRINT     16
 320 GO TO 10                                                           TAUB-1      41
6969 WRITE(6,1420)                                                      CONE3       16
     TAU=ABS(TAU)                                                       CONE3       17
     GO TO 181                                                          CONE3       18
     END                                                                SWIVEL     151
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      SUBROUTINE BLSTWV                                              SWIVEL  152
      REAL MI,MB,M2                                                  SWIVEL  153
      COMMON/BREG/MB,VBN,ETAB,A2,UB,U2,M2                            SWIVEL  154
      COMMON/CONST/G,GP,GM,CON,A1,P1                                 SWIVEL  155
      COMMON/INPUT/MI,XIB,BETA,DELTA                                 SWIVEL  156
      B=CON*BETA                                                     SWIVEL  157
    1 MB=SQRT ((GP*XIB+GM)/(2.*G))                                   SWIVEL  158
      VBN=MB                                                         SWIVEL  159
      ETAB=(GM*XIB+GP)/(GP*XIB+GM)                                   SWIVEL  160
    2 A2=SQRT (XIB*ETAB)                                             SWIVEL  161
      UB=VBN+MI*COS (B)                                              SWIVEL  162
    3 U2=SQRT ((MI*SIN (B))**2+(UB-ETAB*VBN)**2)                     SWIVEL  163
      M2=U2/A2                                                       SWIVEL  164
      RETURN                                                         SWIVEL  165
      END                                                            SWIVEL  166
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      SUBROUTINE BOWANG(M,OELTA,THETA,NERR)                             SWIVEL 167
      REAL M                                                            SWIVEL 169
      COMMON/CONST/G,GP,GM,CON,AI,PI                                    SWIVEL 170
C                                                                       SWIVEL 171
C     SHOCK ANGLE EQUATION IS OF THE FORM OF A BI-CUBIC                 SWIVEL 172
C                                                                       SWIVEL 173
C     OEFINE CONSTANTS AND COEFFICIENTS OF BI-CUBIC                     SWIVEL 174
C                                                                       SWIVEL 175
    5 NERR=0                                                            SWIVEL 176
      OO=CON*OELTA                                                      SWIVEL 177
      SEN=SIN (OD)                                                      SWIVEL 178
      CUS=COS (OO)                                                      SWIVEL 179
      C=-(M**2+2.0)/M**2-G*SEN**2                                       SWIVEL 180
      D=(2.0*M**2+1.0)/M**4+(GP**2/4.0+GM/M**2)*SEN**2                  SWIVEL 181
      E=-CUS**2/M**4                                                    SWIVEL 182
      P=-C*C/3.+O                                                       SWIVEL 183
      Q=2.*(C/3.)**3 -C*O/3. +E                                         SWIVEL 184
    6 R=-O/(2.*(SQRT (-(P/3.)**3)))                                     SWIVEL 185
    7 RABS=ABS (R)                                                      SWIVEL 186
      IF(RABS .GT. 1.) GO TO 140                                        SWIVEL 187
      OMEGA=ACOS  (R)                                                   SWIVEL 188
      CC=2.*SQRT (-P/3.)                                                SWIVEL 189
C                                                                       SWIVEL 190
C     TRIGONOMETRIC SOLUTION TO ROOTS OF CUBIC                          SWIVEL 191
C                                                                       SWIVEL 192
      RT1=CC*COS (OMEGA/3.) -C/3.                                       SWIVEL 193
      RT2= CC*COS (OMEGA/3. +120.*CON   ) -C/3.                         SWIVEL 194
      RT3= CC*COS (OMEGA/3. -120.*CON   ) -C/3.                         SWIVEL 195
C                                                                       SWIVEL 196
C     OETERMINE MIDDLE ROOT - THE PHYSICALLY CORRECT ONE                SWIVEL 197
C     SMALLEST ROOT RESULTS IN AN ENTROPY OECREASE                      SWIVEL 198
C     LARGEST ROOT IS STRONG SHOCK SOLUTION                             SWIVEL 199
C                                                                       SWIVEL 200
      X=AMAX1(RT1,RT2,RT3)                                              SWIVEL 201
      Y=AMIN1(RT1,RT2,RT3)                                              SWIVEL 202
      IF(RT1 .LT. X .AND. RT1 .GT. Y) GO TO 1                           SWIVEL 203
      IF(RT2 .LT. X .AND. RT2 .GT. Y) GO TO 2                           SWIVEL 204
      IF(RT3 .LT. X .AND. RT3 .GT. Y) GO TO 3                           SWIVEL 205
      NEPR=1                                                            SWIVEL 206
      RETURN                                                            SWIVEL 207
    3 RT=RT3                                                            SWIVEL 208
      GO TO 4                                                           SWIVEL 209
    1 RT=RT1                                                            SWIVEL 210
      GO TO 4                                                           SWIVEL 211
    2 RT=RT2                                                            SWIVEL 212
C                                                                       SWIVEL 213
C     SOLUTION FOR SHOCK ANGLE                                          SWIVEL 214
C                                                                       SWIVEL 215
    4 THETA=(ASIN  (SQRT (ABS (RT))))/CON                               SWIVEL 216
  130 IF (THETA-90.0) 150,150,140                                       SWIVEL 217
  140 NERR=1                                                            SWIVEL 218
  150 CONTINUE                                                          SWIVEL 219
      RETURN                                                            SWIVEL 220
      END                                                               SWIVEL 221
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      SUBROUTINE BOWAVE(NERR)                                          SWIVEL   222
      REAL M1,MB,M2                                                    SWIVEL   223
      COMMON/BREG/MB,VBN,ETAB,A2,UB,U2,M2                              SWIVEL   224
      COMMON/CONST/G,GP,GM,CON,A1,P1                                   SWIVEL   225
      COMMON/INPUT/M1,XIB,BETA,DELTA                                   SWIVEL   226
      COMMON/WREG/ THETA,XIW,ETAW,A3,AM3                               JUMP      65
      CALL BOWANG(M1,DELTA,THETA,NERR)                                 SWIVEL   228
      IF (NERR) 10,10,20                                               SWIVEL   229
   10 T=CON*THETA                                                      SWIVEL   230
      D=CON*DELTA                                                      JUMP      66
      AMNS=(M1*SIN(T))**2                                              JUMP      67
      XIW=(2.*G*AMNS-GM)/GP                                            JUMP      68
      AM3=SQRT((1.+0.5*GM*AMNS)/(G*AMNS-0.5*GM))/(SIN(T-D))            JUMP      69
      ETAW=(GM*XIW+GP)/(GP*XIW+GM)                                     SWIVEL   232
      A3=SQRT (XIW*ETAW)                                               SWIVEL   233
   20 CONTINUE                                                         SWIVEL   234
      RETURN                                                           SWIVEL   235
      END                                                              SWIVEL   236
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      SUBROUTINE FINAL(NERR)                                          SWIVEL  237
      REAL M1.MB.M2.LAMBDA                                            SWIVEL  238
      COMMON/BREG/MB.VBN.ETAB.A2.UB.U2.M2                             SWIVEL  239
      COMMON/CONST/G.GP.GM.CON.AI.PI                                  SWIVEL  240
      COMMON/FREG/LAMBDA.DELTAF.THETAF.XIWF.ETAWF.A3F.P3F.U3F         SWIVEL  241
      COMMON/INPUT/M1.XIB.BETA.DELTA                                  SWIVEL  242
      B=CON*BETA                                                      SWIVEL  243
      LAMBDA=BETA-ATAN (M1*SIN (B)/(UB-ETAB*VBN))/CON                 SWIVEL  244
      DELTAF=DELTA+LAMBDA                                             SWIVEL  245
      CALL BOWANG(M2.DELTAF.THETAF.NERR)                              SWIVEL  246
      IF (NERR) 10.10.20                                              SWIVEL  247
   10 T=CON*THETAF                                                    SWIVEL  248
      XIWF=(2.*G*M2*M2*SIN (T)*SIN (T)-GM)/GP                         SWIVEL  249
      ETAWF=(GM*XIWF+GP)/(GP*XIWF+GM)                                 SWIVEL  250
   30 A3F=SQRT (XIWF*ETAWF)*A2                                        SWIVEL  251
      P3F=XIWF*XIB                                                    SWIVEL  252
   40 U3F=SQRT ((U2*COS (T))**2 +(ETAWF*U2*SIN (T))**2)               SWIVEL  253
   20 CONTINUE                                                        SWIVEL  254
      RETURN                                                          SWIVEL  255
      END                                                             SWIVEL  256
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      SUBROUTINE FORFIV(NERR)                                          SWIVEL   257
      REAL MI,MB,M2                                                     SWIVEL   258
      COMMON/APOINT/VA,V1,V2,V3,EPS,ANG1,ANG2,ANG3                      SWIVEL   259
      COMMON/BREG/MB,VBN,ETAB,A2,UB,U2,M2                               SWIVEL   260
      COMMON/CONST/G,GP,GM,CON,AI,PI                                    SWIVEL   261
      COMMON/INPUT/MI,XIB,BETA,DELTA                                    SWIVEL   262
      COMMON/TDREG/THETAT,THETAD,XIT,XID,ANG4,ANG5,ANGT,ANGD,ETAT,      SWIVEL   263
     CA4A3                                                              SWIVEL   264
      COMMON/WREG/ THETA,XIW,ETAW,A3,AM3                                JUMP      70
      P4M=((2.0*G*(V3/A3)**2-GM)/GP)*XIW                                SWIVEL   266
      P5M=((2.0*G*(V2/A2)**2-GM)/GP)*XIB                                SWIVEL   267
      P3=XIW                                                            SWIVEL   268
      P2=XIB                                                            SWIVEL   269
      IF (P4M-P5M) 10,10,20                                             SWIVEL   270
   10 PM=P5M                                                            SWIVEL   271
      GO TO 30                                                          SWIVEL   272
   20 PM=P4M                                                            SWIVEL   273
   30 IF (P3-P2) 40,40,50                                               SWIVEL   274
   40 PL=P2                                                             SWIVEL   275
      A5L=ANG2                                                          SWIVEL   276
      PR=PL/P3                                                          SWIVEL   277
      CALL POINT(PR,V3,A3,DSIG,ANG)                                     SWIVEL   278
      A4L=ANG3-DSIG                                                     SWIVEL   279
      GO TO 60                                                          SWIVEL   280
   50 PL=P3                                                             SWIVEL   281
      A4L=ANG3                                                          SWIVEL   282
      PR=PL/P2                                                          SWIVEL   283
      CALL POINT (PR,V2,A2,DSIG,ANG)                                    SWIVEL   284
      A5L=ANG2+DSIG                                                     SWIVEL   285
   60 CALL INTSEC (P2,P3,ANG2,ANG3,PM,PL,A4L,A5L,V2,A2,V3,A3,NERR)      SWIVEL   286
      IF (NERR) 70,70,80                                                SWIVEL   287
   70 ANGT=ANG3-THETAT                                                  SWIVEL   288
      ANGD=ANG2+THETAD                                                  SWIVEL   289
      ETAT=(GM*XIT+GP)/(GP*XIT+GM)                                      SWIVEL   290
   90 A4A3=SQRT (XIT*ETAT)                                              SWIVEL   291
   80 CONTINUE                                                          SWIVEL   292
      RETURN                                                            SWIVEL   293
      END                                                               SWIVEL   294
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      SUBROUTINE INTSEC (P2,P3,S2,S3,PM,PL,S4L,S5L,V2,A2,V3,A3,NERR)      SWIVEL  295
      COMMON/TDREG/THETAT,THETAD,XIT,XID,ANG4,ANG5,ANGT,ANGD,ETAT,        SWIVEL  296
     CA4A3                                                                SWIVEL  297
      DEL=10.0                                                            SWIVEL  298
      DO 10 I=1,50                                                        SWIVEL  299
      DEL=DEL/10.0                                                        SWIVEL  300
      PU=PL+DEL                                                           SWIVEL  301
      PRT=PU/P3                                                           SWIVEL  302
      PRD=PU/P2                                                           SWIVEL  303
      CALL POINT(PRD,V2,A2,DS,THETAD)                                     SWIVEL  304
      S5U=S2+DS                                                           SWIVEL  305
      CALL POINT(PRT,V3,A3,DS,THETAT)                                     SWIVEL  306
      S4U=S3-DS                                                           SWIVEL  307
      CALL SLIPT(S5L,PL,S5U,PU,S4L,PL,S4U,PU,SO,PO)                       SWIVEL  308
      IF (PO-PU) 10,30,40                                                 SWIVEL  309
   10 CONTINUE                                                            SWIVEL  310
   20 NERR=1                                                              SWIVEL  311
      GO TO 90                                                            SWIVEL  312
   30 XIT=PRT                                                             SWIVEL  313
      XID=PRD                                                             SWIVEL  314
      ANG4=S4U                                                            SWIVEL  315
      ANG5=S5U                                                            SWIVEL  316
      NERR=0                                                              SWIVEL  317
      GO TO 90                                                            SWIVEL  318
   40 DO 70 I=1,1000                                                      SWIVEL  319
      PL=PU                                                               SWIVEL  320
      PU=PO                                                               SWIVEL  321
      S4L=S4U                                                             SWIVEL  322
      S5L=S5U                                                             SWIVEL  323
      PRT=PU/P3                                                           SWIVEL  324
      PRD=PU/P2                                                           SWIVEL  325
      CALL POINT(PRD,V2,A2,DS,THD)                                        SWIVEL  326
      S5U=S2+DS                                                           SWIVEL  327
      CALL POINT(PRT,V3,A3,DS,THT)                                        SWIVEL  328
      S4U=S3-DS                                                           SWIVEL  329
      CALL SLIPT(S5L,PL,S5U,PU,S4L,PL,S4U,PU,SO,PO)                       SWIVEL  330
      IF (PO-PM) 50,20,20                                                 SWIVEL  331
   50 IF (PO-PU) 20,30,60                                                 SWIVEL  332
   60 IF ( ABS (PO-PU)-0.0001) 80,80,70                                   SWIVEL  333
   70 CONTINUE                                                            SWIVEL  334
      GO TO 20                                                            SWIVEL  335
   80 XIT=PO/P3                                                           SWIVEL  336
      XID=PO/P2                                                           SWIVEL  337
      CALL POINT(XID,V2,A2,DS,THETAD)                                     SWIVEL  338
      ANG5=S2+DS                                                          SWIVEL  339
      CALL POINT(XIT,V3,A3,DS,THETAT)                                     SWIVEL  340
      ANG4=S3-DS                                                          SWIVEL  341
      NERR=0                                                              SWIVEL  342
   90 CONTINUE                                                            SWIVEL  343
      RETURN                                                              SWIVEL  344
      END                                                                 SWIVEL  345
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      SUBROUTINE POINT(XI,V,A,DEL,ANG)                    SWIVEL   346
      COMMON/CONST/G,GP,GM,CON,AI,PI                      SWIVEL   347
      AA=2.*G*((V/A)*(V/A)-1.)/GP                         SWIVEL   348
      BB=XI-1.                                            SWIVEL   349
      CC=XI*GM/GP                                         SWIVEL   350
      PWR=(AA-BB)/CC                                      SWIVEL   351
      PWR=ABS (PWR)                                       SWIVEL   352
    1 COANG=SQRT (PWR)                                    SWIVEL   353
      AA=G*(V/A)*(V/A)                                    SWIVEL   354
      DEL=ATAN (BB*COANG/(AA-BB))/CON                     SWIVEL   355
      ANG=ATAN (1./COANG)/CON                             SWIVEL   356
      RETURN                                              SWIVEL   357
      END                                                 SWIVEL   358
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      SUBROUTINE POINTA(ICASE)                                 SWIVEL    359
      REAL MI,MB,M2                                            SWIVEL    360
      COMMON/APOINT/VA,VI,V2,V3,EPS,ANG1,ANG2,ANG3             SWIVEL    361
      COMMON/BREG/MB,VBN,ETAB,A2,UB,U2,M2                      SWIVEL    362
      COMMON/CONST/G,GP,GM,CON,AI,PI                           SWIVEL    363
      COMMON/INPUT/MI,XIB,BETA,DELTA                           SWIVEL    364
      COMMON/WREG/ THETA,XIW,ETAW,A3,AM3                       JUMP       71
      B=CON*BETA                                               SWIVEL    366
      T=CON*THETA                                              SWIVEL    367
      ANG=90.-THETA                                            SWIVEL    368
      IF(BETA-ANG)10,10,20                                     SWIVEL    369
   10 ICASE=1                                                  SWIVEL    370
      VA=UB/COS (B+T)                                          SWIVEL    371
   40 VI=SQRT ((MI*SIN (T))**2+(VA-MI*COS (T))**2)             SWIVEL    372
      V2=SQRT ((ETAB*VBN)**2+(VA*SIN (B+T)-MI*SIN (B))**2)     SWIVEL    373
      V3=SQRT ((ETAW*MI*SIN (T))**2+(VA-MI*COS (T))**2)        SWIVEL    374
      EPS=ATAN (MI*SIN (T)/(VA-MI*COS (T)))/CON                SWIVEL    375
      ANG1=90.-THETA-EPS                                       SWIVEL    376
      A=CON*(90.-BETA-THETA-EPS)                               SWIVEL    377
      ANG2=BETA+ATAN (ETAB*TAN (A))/CON                        SWIVEL    378
      E=CON*EPS                                                SWIVEL    379
      ANG3=90.-THETA-ATAN (ETAW*TAN (E))/CON                   SWIVEL    380
      GO TO 30                                                 SWIVEL    381
   20 ICASE=2                                                  SWIVEL    382
      VA=-UB/COS (B+T)                                         SWIVEL    383
   50 VI=SQRT ((MI*SIN (T))**2+(VA+MI*COS (T)**2) )            SWIVEL    384
      V2=SQRT ((ETAB*VBN)**2+(VA*SIN (B+T)+MI*SIN (B))**2)     SWIVEL    385
      V3=SQRT ((ETAW*MI*SIN (T))**2+(VA+MI*COS (T))**2)        SWIVEL    386
      EPS=ATAN (MI*SIN (T)/(VA+MI*COS (T)))/CON                SWIVEL    387
      ANG1=THETA-EPS                                           SWIVEL    388
      A=CON*(BETA+THETA-EPS-90.)                               SWIVEL    389
      ANG2=90.-BETA+ATAN (ETAB*TAN (A))/CON                    SWIVEL    390
      E=CON*EPS                                                SWIVEL    391
      ANG3=THETA-ATAN (ETAW*TAN (E))/CON                       SWIVEL    392
   30 CONTINUE                                                 SWIVEL    393
      RETURN                                                   SWIVEL    394
      END                                                      SWIVEL    395
```

```
      SUBROUTINE REGRFL(ICASE,NERR)                                     SWIVEL  396
      REAL M1,M4P,LAMBDA                                                SWIVEL  397
      COMMON/APOINT/VA,V1,V2,V3,EPS,ANG1,ANG2,ANG3                      SWIVEL  398
      COMMON/CONST/G,GP,GM,CON,A1,P1                                    SWIVEL  399
      COMMON/FREG/LAMBDA,DELTAF,THETAF,XIWF,ETAWF,A3F,P3F,U3F           SWIVEL  400
      COMMON/INPUT/M1,XIB,BETA,DELTA                                    SWIVEL  401
      COMMON/RREG/OMEGAI,DELTAR,V4P,M4P,THETAR ,OMEGAR,XIR,P6,P6P3,P6P3FSWIVEL  402
      COMMON/TDREG/THETAT,THETAD,XIT,XID,ANG4,ANG5,ANGT,ANGD,ETAT,      SWIVEL  403
     CA4A3                                                              SWIVEL  404
      COMMON/WREG/ THETA,XIW,ETAW,A3,AM3                                JUMP     72
    1 GO TO (10,20),ICASE                                               SWIVEL  406
   10 OMEGAI=90.-DELTA-ANGT                                             SWIVEL  407
      GO TO 30                                                          SWIVEL  408
   20 OMEGAI=ABS (DELTA-ANGT)                                           SWIVEL  409
   30 O=CON*OMEGAI                                                      SWIVEL  410
      T=CON*THETAT                                                      SWIVEL  411
      DELTAR=OMEGAI-ATAN (ETAT*TAN (O))/CON                             SWIVEL  412
   60 V4P=V3*SIN (T)*SQRT (ETAT**2+(1./TAN (O))**2)                     SWIVEL  413
      M4P=V4P/(A4A3*A3)                                                 SWIVEL  414
      IF((OMEGAI-.02) .LT. 0.) GO TO 70                                 CONE3    19
      CALL BOWANG(M4P,DELTAR,THETAR ,NERR)                              SWIVEL  415
      IF (NERR) 40,40,50                                                SWIVEL  416
   40 T=CON*THETAR                                                      SWIVEL  417
      OMEGAR=THETAR -DELTAR                                             SWIVEL  418
      XIR=(2.*G*M4P*M4P*SIN (T)*SIN (T)-GM)/GP                          SWIVEL  419
   80 CONTINUE                                                          CONE3    20
      P6=XIR*XIT*XIW                                                    SWIVEL  420
      P6P3=XIR*XIT                                                      SWIVEL  421
      P6P3F=P6/P3F                                                      SWIVEL  422
   50 CONTINUE                                                          SWIVEL  423
      RETURN                                                            SWIVEL  424
   70 PRINT 100                                                         CONE3    21
  100 FORMAT(1H0    *TRANSMITTED BLAST WAVE PARALLEL TO BODY - IGNORE VECONE3    22
     1LOCITY AND TIME OUTPUTS*,/)                                       CONE3    23
      OMEGAR=0.00001                                                    CONE3    24
      OMEGAI=0.00001                                                    CONE3    25
      THETAR=0.00001                                                    CONE3    26
      DELTAR=0.00001                                                    CONE3    27
      XIR=((3.*G-1.)*XIT-GM)/(GM*XIT+GP)                                CONE3    28
      GO TO 80                                                          CONE3    29
      END                                                               SWIVEL  425
```

```
      SUBROUTINE SLIPT(X1,Y1,X2,Y2,X3,Y3,X4,Y4,X,Y)                    SWIVEL   426
      A=(Y1-Y2)/(X1-X2)                                                 SWIVEL   427
      B=0.5*(Y1+Y2-A*(X1+X2))                                           SWIVEL   428
      C=(Y3-Y4)/(X3-X4)                                                 SWIVEL   429
      D=0.5*(Y3+Y4-C*(X3+X4))                                           SWIVEL   430
      X=(D-B)/(A-C)                                                     SWIVEL   431
      Y=0.5*(B+D+X*(A+C))                                               SWIVEL   432
      RETURN                                                            SWIVEL   433
      END                                                               SWIVEL   434
```

```
      SUBROUTINE TIMEA(NERR)                                            SWIVEL  435
      REAL M1,M4P,LAMBDA,MU7                                            SWIVEL  436
      COMMON/APOINT/VA,V1,V2,V3,EPS,ANG1,ANG2,ANG3                      SWIVEL  437
      COMMON/CONST/G,GP,GM,CON,AI,PI                                    SWIVEL  438
      COMMON/FREG/LAMBDA,DELTAF,THETAF,XIWF,ETAWF,A3F,P3F,U3F           SWIVEL  439
      COMMON/INPUT/M1,XIB,BETA,DELTA                                    SWIVEL  440
      COMMON/RREG/OMEGAI,DELTAR,V4P,M4P,THETAR ,OMEGAR,XIR,P6,P6P3,P6P3FSWIVEL  441
      COMMON/TOREG/THETAT,THETAU,XIT,XID,ANG4,ANG5,ANGI,ANGO,ETAT,      SWIVEL  442
     CA4A3                                                              SWIVEL  443
      COMMON/TIME/APOR,CPOR,CHI,OCOR,VC,PSI7,U7,V7,MU7,PSIM,EPOR,VE,    SWIVEL  444
     COPOR,TAU                                                          SWIVEL  445
      COMMON/WREG/ THETA,XIW,ETAW,A3,AM3                                JUMP     73
  100 FORMAT(//,39X,45HMACH ANGLE SET TO 90 DEGREES. ERROR PROBABLE.)   SPACE     2
      T=CON*THETA                                                       SWIVEL  448
      D=CON*DELTA                                                       SWIVEL  449
      AT=CON*ANGT                                                       SWIVEL  450
      AO=CON*ANGO                                                       SWIVEL  451
      O=CON*OMEGAR                                                      SWIVEL  452
      OI=CON*OMEGAI                                                     SWIVEL  453
      APOR=SIN (T-O)/SIN (OI)                                           SWIVEL  454
      CPOR=APOR*SIN (AO-AT)/COS (AO+U-O)                                SWIVEL  455
      AA=SIN (T)-APOR*COS (AT)+CPOR*SIN (U-D)                           SWIVEL  456
      BB=COS (T)-APOR*SIN (AT)-CPOR*COS (U-D)                           SWIVEL  457
      CHI=ATAN (AA/BB)/CON                                              SWIVEL  458
      C=CON*CHI                                                         SWIVEL  459
      OCOR=SQRT (AA*AA+BB*BB)                                           SWIVEL  460
      VC=OCOR*VA                                                        SWIVEL  461
      U7=U3F                                                            SWIVEL  462
      AA=VC*SIN (C)-U7*SIN (D)                                          SWIVEL  463
      BB=VC*COS (C)-U7*COS (D)                                          SWIVEL  464
      PSI7=ATAN (AA/BB)/CON                                             SWIVEL  465
      V7=SQRT (AA*AA+BB*BB)                                             SWIVEL  466
      CNST=A3F/V7                                                       SWIVEL  467
      IF(CNST .LE. 1.) GO TO 1                                          SWIVEL  468
      CNST=1.                                                           SWIVEL  469
      WRITE(6,100)                                                      SWIVEL  470
    1 MU7=ASIN  (CNST)/CON                                              SWIVEL  471
      PSIM=PSI7+MU7                                                     SWIVEL  472
      PM=CON*PSIM                                                       SWIVEL  473
      EPOR=CPOR*SIN (O+PM-D)/SIN (PM-D)                                 SWIVEL  474
      AA=COS (T)-APOR*SIN (AT)                                          SWIVEL  475
      OPOR=AA/COS (D)                                                   SWIVEL  476
      VE=(OPOR-EPOR)*VA                                                 SWIVEL  477
      TAU=EPOR/(AA*VE)                                                  SWIVEL  478
      IF(TAU .LE. 0.) NERR=1                                            SWIVEL  479
      RETURN                                                            SWIVEL  480
      END                                                               SWIVEL  481
```

```
      SUBROUTINE TIMEB(NERR)                                            SWIVEL   482
      REAL MI,M4P,LAMBDA,MU7                                            SWIVEL   483
      COMMON/APOINT/VA,VI,V2,V3,EPS,ANGI,ANG2,ANG3                      SWIVEL   484
      COMMON/CONST/G,GP,GM,CON,AI,PI                                    SWIVEL   485
      COMMON/FREG/LAMBDA,DELTAF,THETAF,XIWF,ETAWF,A3F,P3F,U3F           SWIVEL   486
      COMMON/INPUT/MI,XIB,BETA,DELTA                                    SWIVEL   487
      COMMON/RREG/OMEGAI,DELTAR,V4P,M4P,THETAR ,OMEGAR,XIR,P6,P6P3,P6P3F SWIVEL   488
      COMMON/TOREG/THETAI,THETAD,XIT,XID,ANG4,ANG5,ANGT,ANGO,ETAT,      SWIVEL   489
     CA4A3                                                              SWIVEL   490
      COMMON/TIME/APOR,CPOR,CHI,OCOR,VC,PSI7,U7,V7,MU7,PSIM,EPOR,VE,    SWIVEL   491
     COPOR,TAU                                                          SWIVEL   492
      COMMON/WREG/ THETA,XIW,ETAW,A3,AM3                                JUMP      74
  100 FORMAT(//,39X,45HMACH ANGLE SE( TO 90 DEGREES. ERROR PROBABLE.)   SPACE      3
      T=CON*THETA                                                       SWIVEL   495
      O=CON*DELTA                                                       SWIVEL   496
      AT=CON*ANGT                                                       SWIVEL   497
      AD=CON*ANGO                                                       SWIVEL   498
      O=CON*OMEGAR                                                      SWIVEL   499
      OI=CON*OMEGAI                                                     SWIVEL   500
      IF(DELTA-ANGT) 10,10,20                                           SWIVEL   501
   10 NERR=1                                                            SWIVEL   502
      GO TO 30                                                          SWIVEL   503
   20 NERR=0                                                            SWIVEL   504
      APOR=SIN (T-D)/SIN (OI)                                           SWIVEL   505
      CPOR=APOR*SIN (AO-AT)/SIN (O+D-AD)                                SWIVEL   506
      AA=SIN (T)+APOR*SIN (AT)+CPOR*SIN (O+O)                           SWIVEL   507
      BB=COS (T)+APOR*COS (AT)+CPOR*COS (O+D)                           SWIVEL   508
      CHI=ATAN (AA/BB)/CON                                              SWIVEL   509
      C=CON*CHI                                                         SWIVEL   510
      OCOR=SQRT (AA*AA+BB*BB)                                           SWIVEL   511
      VC=OCOR*VA                                                        SWIVEL   512
      U7=U3F                                                            SWIVEL   513
      AA=VC*SIN (C)+U7*SIN (O)                                          SWIVEL   514
      BB=VC*COS (C)+U7*COS (O)                                          SWIVEL   515
      PSI7=ATAN (AA/BB)/CON                                             SWIVEL   516
      V7=SQRT (AA*AA+BB*BB)                                             SWIVEL   517
      CNST=A3F/V7                                                       SWIVEL   518
      IF(CNST .LE. 1.) GO TO 1                                          SWIVEL   519
      CNST=1.                                                           SWIVEL   520
      WRITE(6,100)                                                      SWIVEL   521
    1 MU7=ASIN  (CNST)/CON                                              SWIVEL   522
      PSIM=PSI7-MU7                                                     SWIVEL   523
      PM=CON*PSIM                                                       SWIVEL   524
      AA=COS (T)+APOR*COS (AT)                                          SWIVEL   525
      TAU=CPOR*SIN (O+D-PM)/(AA*SIN (C-PM)*VC)                          SWIVEL   526
      IF(TAU .LE. 0.) NERR=1                                            SWIVEL   527
   30 CONTINUE                                                          SWIVEL   528
      RETURN                                                            SWIVEL   529
      END                                                               SWIVEL   530
```

```
      SUBROUTINE WEDGE (XII,MI,DELTA,THETA)                             SWIVEL   531
C                                                                       SWIVEL   532
C     THIS CODE COMPUTES THE WEDGE AND SHOCK ANGLE WHEN THE WEDGE       SWIVEL   533
C     SURFACE PRESSURE RATIO AND THE AMBIENT MACH NUMBER ARE SPECIFIED  SWIVEL   534
C                                                                       SWIVEL   535
      REAL MS, MI                                                       SWIVEL   536
C                                                                       SWIVEL   537
      MS=MI*MI                                                          SWIVEL   538
      THETA=ASIN  (SQRT ((6.*XII+1.)/(7.*MS)))                          SWIVEL   539
C                                                                       SWIVEL   540
      DELTA=ATAN(1./TAN(THETA)*5.*(MS*SIN(THETA)*SIN(THETA)-1.)/(6.*M   SWIVEL   541
     CS- 5.*(MS*SIN (THETA)*SIN (THETA)-1.)))                           SWIVEL   542
C                                                                       SWIVEL   543
    1 THETA=THETA*57.296                                                SWIVEL   544
C                                                                       SWIVEL   545
      DELTA=DELTA*57.296                                                SWIVEL   546
C                                                                       SWIVEL   547
      RETURN                                                            SWIVEL   548
      END                                                               SWIVEL   549
```

```
      SUBROUTINE PARA (Y1,Y2,Y3,X1,X2,X3,CON1,CON2,CON3)               SWIVEL   550
      CON2=((X2*X2-X3*X3)*(Y1-Y2)-(X1*X1-X2*X2)*(Y2-Y3))/               SWIVEL   551
     C ((X2*X2-X3*X3)*(X1-X2)-(X1*X1-X2*X2)*(X2-X3))                    SWIVEL   552
      CON3=((Y1-Y2)-CON2*(X1-X2))/(X1*X1-X2*X2)                         SWIVEL   553
      CON1=Y1-CON2*X1-CON3*X1*X1                                        SWIVEL   554
      RETURN                                                            SWIVEL   555
      END                                                               SWIVEL   556
```

```
      SUBROUTINE FCONE(CONE,XIBS,MIS)                                  NUCONE  41
C                                                                      NUCONE  42
C     ESTIMATES OF FINAL CONDITIONS FOR CONES AT ANGLE OF ATTACK       NUCONE  43
C                                                                      NUCONE  44
      REAL M1,MB,M2,LAMBDA                                             NUCONE  45
      REAL MIS                                                         NUCONE  46
      COMMON/BSAVE/BM,SVBN,SETAB,SA2,SUB,SU2,SM2,BETAS                 NUCONE  47
      COMMON/CONST/ G,GP,GM,CON,A1,P1                                  NUCONE  48
      COMMON/FREG/ LAMBDA,DELTAF,THETAF,XIWF,ETAWF,A3F,P3F,U3F         NUCONE  49
C                                                                      NUCONE  50
C     CURVE FITS HAVE NOT BEEN CHECKED OUT FOR MACH NO. + 3 OR CONE    NUCONE  51
C     ANGLES > 15 DEG.                                                 NUCONE  52
C                                                                      NUCONE  53
      UB=SUB                                                           NUCONE  54
      VBN=SVBN                                                         NUCONE  55
      ETAB=SETAB                                                       NUCONE  56
      M2=SM2                                                           NUCONE  57
      MB=BM                                                            NUCONE  58
      A2=SA2                                                           NUCONE  59
      U2=SU2                                                           NUCONE  60
      BETA=BETAS                                                       NUCONE  61
      DELTA=CONE                                                       NUCONE  62
      B=CON*BETA                                                       NUCONE  63
      LAMBDA=BETA-ATAN(MIS*SIN(B)/(UB-ETAB*VBN))/CON                   NUCONE  64
      ALFA=LAMBDA                                                      NUCONE  65
      AL=CON*ALFA                                                      NUCONE  66
      CN=CON*DELTA                                                     NUCONE  67
      AMS=M2**2                                                        NUCONE  68
      SNA=SIN(CN+AL)                                                   NUCONE  69
      SN=SIN(CN)                                                       NUCONE  70
      CS=COS(CN)                                                       NUCONE  71
      SNS=SN**2                                                        NUCONE  72
      HSF=M2*SN                                                        NUCONE  73
      AKC=HSF**2                                                       NUCONE  74
      X=SQRT((GP/2.)*AKC+1.)                                           NUCONE  75
C                                                                      NUCONE  76
C     NEWTONIAN PRESSURE COEFFICIENT                                   NUCONE  77
C                                                                      NUCONE  78
      CPN=2.*(SNA**2)                                                  NUCONE  79
C                                                                      NUCONE  80
C     CURVE FIT TO INVISCID PRESSURE AT ANGLE OF ATTACK                NUCONE  81
C                                                                      NUCONE  82
      CP=CPN+0.42*SNA/M2                                               NUCONE  83
      XIWF=0.5*G*AMS*CP+1.                                             NUCONE  84
      P3F=XIWF*XIBS                                                    NUCONE  85
C                                                                      NUCONE  88
C     CURVE FIT TO SMALL ANGLES BOW SHOCK YAW RATIO                    NUCONE  89
C                                                                      NUCONE  90
      OMHA=1.43*EXP(-1.59*HSF)                                         NUCONE  91
C                                                                      NUCONE  92
C     ZERO ANGLE OF ATTACK BOW SHOCK ANGLE                             NUCONE  93
C                                                                      NUCONE  94
      THETA0=(ASIN((-0.01617+X)/M2))/CON                               NUCONE  95
C                                                                      NUCONE  96
C     WINDWARD RAY SHOCK ANGLE                                         NUCONE  97
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SUBROUTINE  FCONE     TRACE                    CDC 6600 FTN V3.0-P304 OPT=1  10/25/73  14.09.27.     PAGE    2

            C                                                               NUCONE    98
                  THETAF=THETAO-ALFA*OMMA                                   NUCONE    99
                  IF(THETAF .LT. DELTA) THETAF=DELTA                        NUCONE   100
                  IF(ALFA .GE. DELTA) WRITE(6,100)                          NUCONE   101
              100 FORMAT(//,20X,41HSMALL ANGLE OF ATTACK ASSUMPTION VIOLATED.)  NUCONE   102
            C                                                               NUCONE   103
            C     CONE SURFACE DENSITY                                      NUCONE   104
            C                                                               NUCONE   105
                  STAL=SIN(THETAF*CON)                                      NUCONE   106
                  HSP=M2*M2*STAL*STAL                                       NUCONE   107
                  P3SP2=1.+2.*G*(ABS(HSP-1.))/GP                            NUCONE   108
                  R3SH2=GP*HSP/(GM*HSP+2.)                                  NUCONE   109
                  RC=(R3SH2*G/ETAB)*(P3F/(P3SP2*XIBS))**(1./G)              NUCONE   110
                  ETAWF=(G/ETAB)/RC                                         NUCONE   111
            C                                                               NUCONE   112
            C     SURFACE SOUND SPEED                                       NUCONE   113
            C                                                               NUCONE   114
                  A3F=SQRT(G*P3F/RC)                                        NUCONE   115
            C                                                               NUCONE   116
            C     CURVE FIT TO SURFACE MACH NO. AT ANGLE OF ATTACK          NUCONE   117
            C                                                               NUCONE   118
            C     ZERO ANGLE OF ATTACK TERM                                 NUCONE   119
            C                                                               NUCONE   120
                  AM1M2=CS*CS*(1.025-0.16*HSF)                              NUCONE   121
                  IF(AM1M2 .GT. 1.) AM1M2=1.                                NUCONE   122
            C                                                               NUCONE   123
            C     ANGLE OF ATTACK TERM                                      NUCONE   124
            C                                                               NUCONE   125
                  AM2M2=2.8*SN*SN*(HSF**(-1.107))                           NUCONE   126
                  IF(AM2M2 .GT. 1.) AM2M2=1.                                NUCONE   127
            C                                                               NUCONE   128
            C     WINDWARD RAY SURFACE VELOCITY                             NUCONE   129
            C                                                               NUCONE   130
                  CNST=SQRT(2./GP+(GM/GP)*M2)                               NUCONE   131
                  U3F=M2*A2*CNST*(AM1M2-AL*AM2M2)                           NUCONE   132
            C                                                               NUCONE   133
                  DELTAF=CONE                                               NUCONE   134
            C                                                               NUCONE   135
                  RETURN                                                    NUCONE   136
                  END                                                       NUCONE   137
```
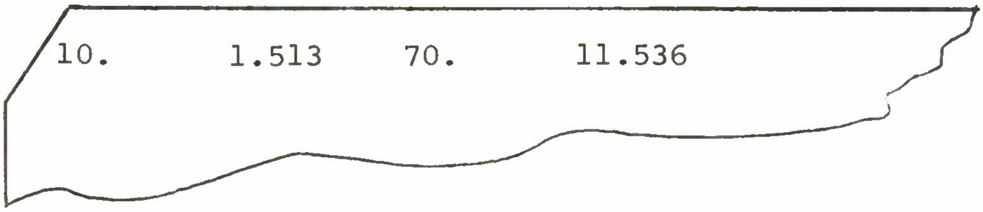

CHECK CASES FOR PRIMUS

1. Wedge

   Flight Mach Number = 10., Wedge Angle=11.536°
   Blast Pressure Ratio = 1.513, Intercept Angle=70°

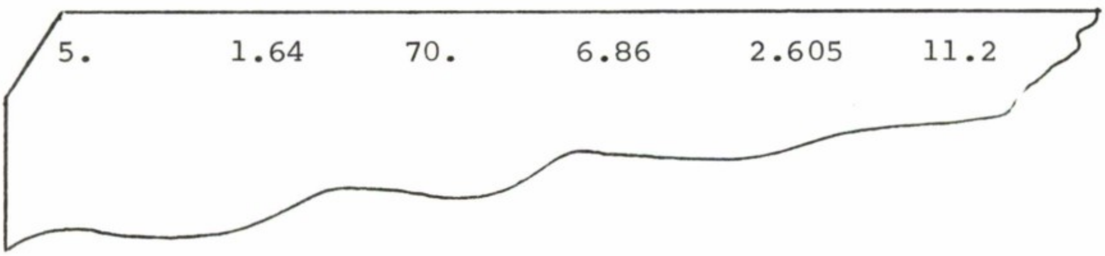
INPUT CARD



2. Cone (flow deflection at shock specified)

   Flight Mach Number = 5., Cone Semi-Angle=11.2°
   Blast Pressure Ratio = 1.64, Intercept Angle=70°

INPUT CARD



OBLIQUE BLAST WAVE REFLECTION FROM WEDGE OR CONE IN SUPERSONIC FLOW

INPUT CONDITIONS-

MSUB1	XISUBB	BETA(DEG)	DELTA(DEG)
10.00000	1.51300	70.00000	11.53600

CONSTANTS-

GAMMA	ASUB1	PSUB1
1.40000	1.00000	1.00000

CONDITIONS ACROSS BLAST WAVE-

MSUBB	VSUBBN	ETASUBB	ASUB2	USUBB	USUB2	MSUB2
1.19988	1.19988	.74549	1.06204	4.62008	10.10852	9.51807

NEW STEADY STATE CONDITIONS, (F), ATTACHED FINAL BOW SHOCK-

LAMBDA(DEG)	DELTAF(DEG)	THETAF(DEG)	XISUBWF	ETASUBWF	ASUB3F	PSUB3F	USUB3F
1.62679	13.16279	18.05207	9.98260	.26246	1.71906	15.10367	9.64603

CONDITIONS ACROSS BOW WAVE, ATTACHED BOW SHOCK-

THETA(DEG)	XISUBW	ETASUBW	ASUB3	MSUB3
16.07256	8.77565	.27539	1.55458	6.20061

STEADY CONDITIONS FOR POINT A-

VSUBA	VSUB1	VSUB2	VSUB3	EPSA(DEG)	SIGMA1(DEG)	SIGMA2(DEG)	SIGMA3(DEG)
67.45333	57.91043	57.90491	57.84924	2.74020	71.18723	70.88512	73.17228

CONDITIONS IN REGIONS 4 AND 5-

THETAT(DEG)	THETAD(DEG)	XISUBT	XISUBD	SIGMA4(DEG)	SIGMA5(DEG)	PHIT(DEG)	PHID(DEG)	ETASUBT	A4/A3
1.75300	2.74748	1.34515	7.80210	72.83893	72.83893	71.41929	73.63260	.80975	1.04366

CONDITIONS OF REGULAR REFLECTION-

OMEGAI(DEG)	DELTAR(DEG)	VSUB4P	MSUB4P	THETARP(DEG)	OMEGAR(DEG)	XISUBR	PSUB6	P6/P3	P6/P3F
7.04471	1.33037	14.39180	8.87038	7.33142	6.00105	1.32816	15.67939	1.78658	1.03805

NOMINAL TIME OF PEAK OVERPRESSURE-

AP/R	CP/R	OC/R	EP/R	OP/R
.04492	.13253	.22544	.15849	.35682

CHI(DEG)	PSI7(DEG)	MU7(DEG)	PSIM(DEG)
15.05949	21.12487	17.84243	38.96730

VSUBC	USUB7	VSUB7	VSUBE	TAU
15.20690	9.64603	5.61051	13.37757	.03389

OBLIQUE BLAST WAVE REFLECTION FROM WEDGE OR CONE IN SUPERSONIC FLOW

INPUT CONDITIONS-

MSUB1	XISUBB	BETA(DEG)	DELTA(DEG)
5.00000	1.64000	70.00000	6.86000

CONSTANTS-

GAMMA	ASUB1	PSUB1
1.40000	1.00000	1.00000

CONDITIONS ACROSS BLAST WAVE-

MSUBB	VSUBBN	ETASUBB	ASUB2	USUBB	USUB2	MSUB2
1.24442	1.24442	.70480	1.07511	2.95452	5.13725	4.77834

NEW STEADY STATE CONDITIONS, (F), ATTACHED FINAL BOW SHOCK-

LAMBDA(DEG)	DEL(AF(DEG)	THETAF(DEG)	XISUBWF	ETASUBWF	ASUB3F	PSUB3F	USUB3F
3.85293	10.71293	20.55649	3.11760	.46269	1.29125	5.11287	4.88202

CONDITIONS ACROSS BOW WAVE, ATTACHED BOW SHOCK-

THETA(DEG)	XISUBW	ETASUBW	ASUB3	MSUB3
16.58992	2.21104	.57556	1.12809	4.30977

STEADY CONDITIONS FOR POINT A-

VSUBA	VSUB1	VSUB2	VSUB3	EPSA(DEG)	SIGMA1(DEG)	SIGMA2(DEG)	SIGMA3(DEG)
49.67075	44.90159	44.89291	44.88641	1.82197	71.58812	71.11944	72.36120

CONDITIONS IN REGIONS 4 AND 5-

THETAT(DEG)	THETAD(DEG)	XISUBT	XISUBD	SIGMA4(DEG)	SIGMA5(DEG)	PHIT(DEG)	PHID(DEG)	ETASUBT	A4/A3
1.74970	1.91164	1.55536	2.09693	71.89115	71.89115	70.61150	73.03108	.73125	1.06647

THIS CASE IS BEING COMPUTED FOR A CONE

SINGLE STEP SHOCK COMPRESSION TO CONE SURFACE PRESSURE

PCONE/PSHOCK	MSUB1W	SHOCK ANGLE	DEFL. ANGLE	ENTROPY JUMP	BLAST ANGLE
1.1782	4.3098	14.425	1.5364	.57720E-03	70.611

OBLIQUE BLAST WAVE REFLECTION FROM WEDGE OR CONE IN SUPERSONIC FLOW

INPUT CONDITIONS-

MSUB1	XISUBB	BETA(DEG)	DELTA(DEG)
4.30977	1.55536	70.61150	1.53638

CONSTANTS-

GAMMA	ASUB1	PSUB1
1.40000	1.00000	1.00000

CONDITIONS ACROSS BLAST WAVE-

MSUBB	VSUBBN	ETASUBB	ASUB2	USUBB	USUB2	MSUB2
1.21492	1.21492	.73125	1.06647	2.64564	4.42889	4.15286

NEW STEADY STATE CONDITIONS. (F). ATTACHED FINAL BOW SHOCK-

LAMBDA(DEG)	DELTAF(DEG)	THETAF(DEG)	XISUBWF	ETASUBWF	ASUB3F	PSUB3F	USUB3F
3.98770	5.52408	17.88335	1.73067	.67908	1.15615	2.69181	4.31490

CONDITIONS ACROSS BOW WAVE. ATTACHED BOW SHOCK-

THETA(DEG)	XISUBW	ETASUBW	ASUB3	MSUB3
14.42542	1.17818	.88959	1.02377	4.18238

STEADY CONDITIONS FOR POINT A-

VSUBA	VSUB1	VSUB2	VSUB3	EPSA(DEG)	SIGMA1(DEG)	SIGMA2(DEG)	SIGMA3(DEG)
30.58057	26.42849	26.41549	26.42394	2.32826	73.24631	72.53883	73.50313

CONDITIONS IN REGIONS 4 AND 5-

THETAT(DEG)	THETAD(DEG)	XISUBT	XISUBD	SIGMA4(DEG)	SIGMA5(DEG)	PHIT(DEG)	PHID(DEG)	ETASUBT	A4/A3
2.68572	2.47341	1.53980	1.16639	72.79583	72.79583	70.81742	75.01225	.73640	1.06485

THIS CASE IS BEING COMPUTED FOR A CONE

NEW STEADY STATE CONDITIONS. (F). ATTACHED FINAL BOW SHOCK-

LAMBDA(DEG)	DELTAF(DEG)	THETAF(DEG)	XISUBWF	ETASUBWF	ASUB3F	PSUB3F	USUB3F
3.85293	11.20000	15.90160	3.52093	.40957	1.29105	5.77432	5.48085

CONDITIONS OF REGULAR REFLECTION- .

OMEGAI(DEG)	DELTAR(DEG)	VSUB4P	MSUB4P	THETARP(DEG)	OMEGAR(DEG)	XISUBR	PSUB6	P6/P3	P6/P3F
7.98258	2.08681	8.87637	8.14231	8.43865	6.35184	1.49904	2.71949	2.30822	1.04132

CONE RESULTS ARE

MSUBF	THETAC	ALPHAFC	CONANGL	PC/P1	P6/PC	PSUB6	PSCALE	IMSCALE	TAU
4.245256	15.901597	3.852930	11.200000	2.604999	2.308223	6.012918	2.211044	1.128087	.047.

DENSITY VARIATION ACROSS SHOCK LAYER

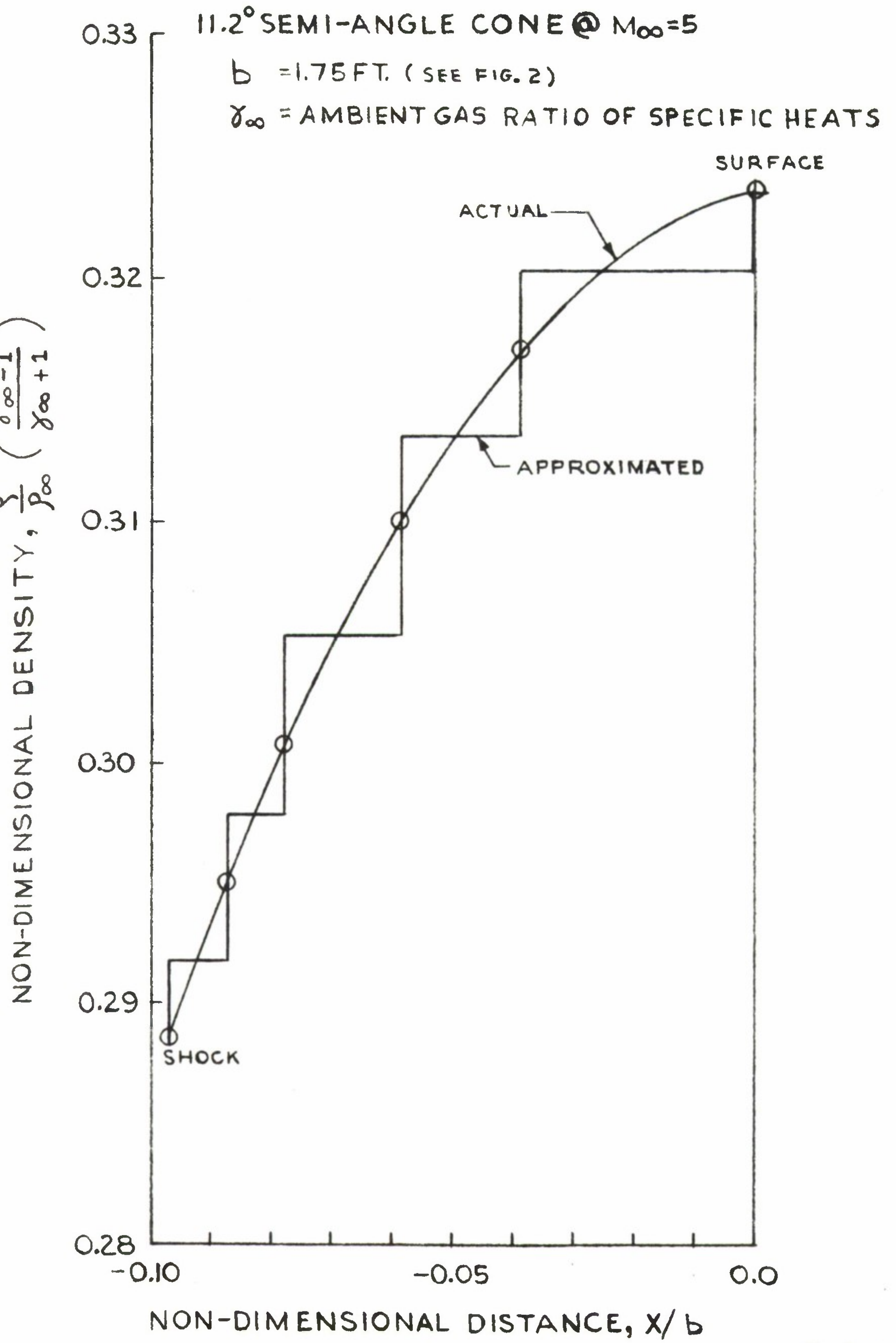
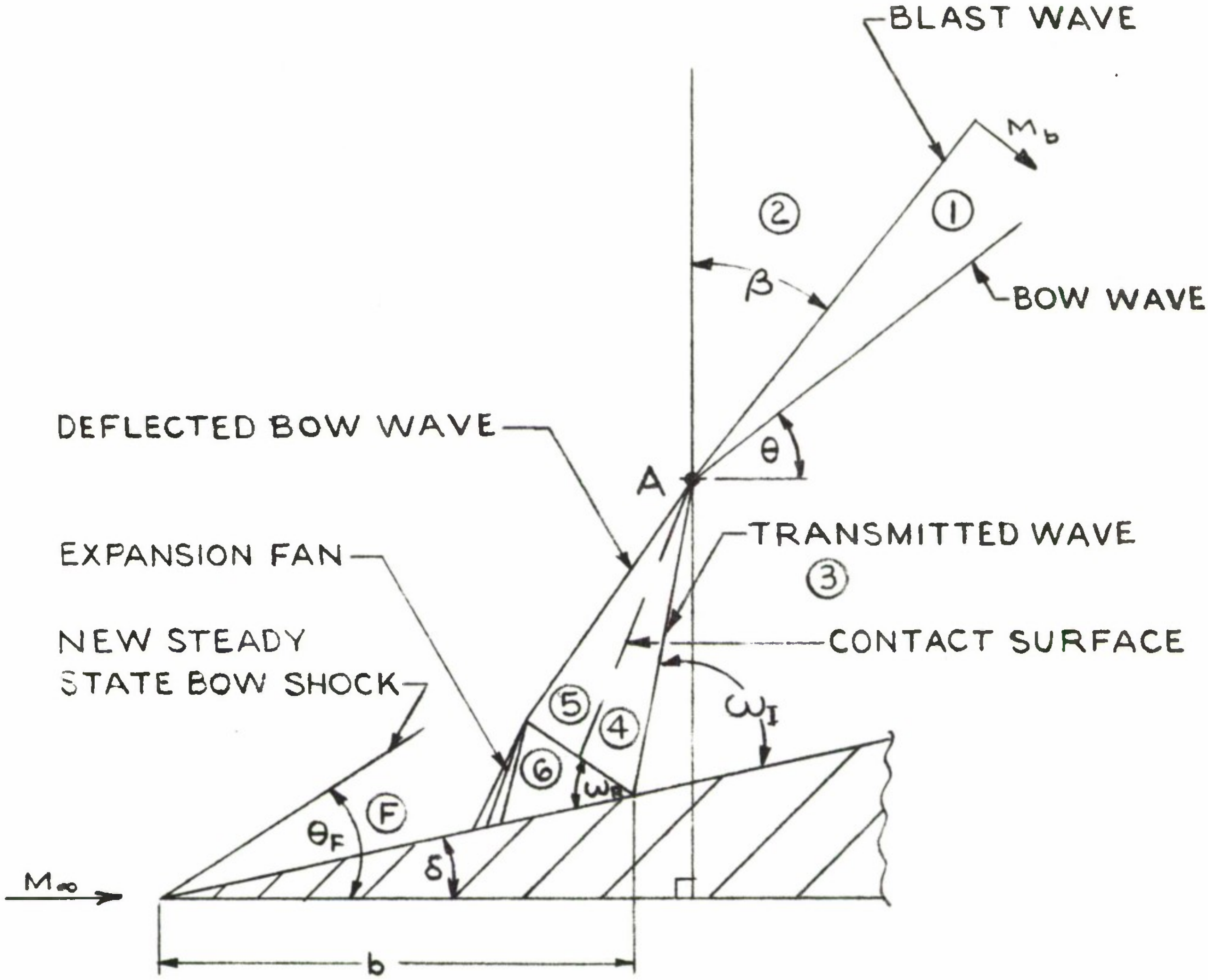


FIG. 1



BASIC GEOMETRY AND NOMENCLATURE OF 2-D ANALYSIS

FIG. 2.

McDONNELL-DOUGLAS PREDICTION OF MACH REFLECTION BOUNDS FOR DNA SLED TEST.

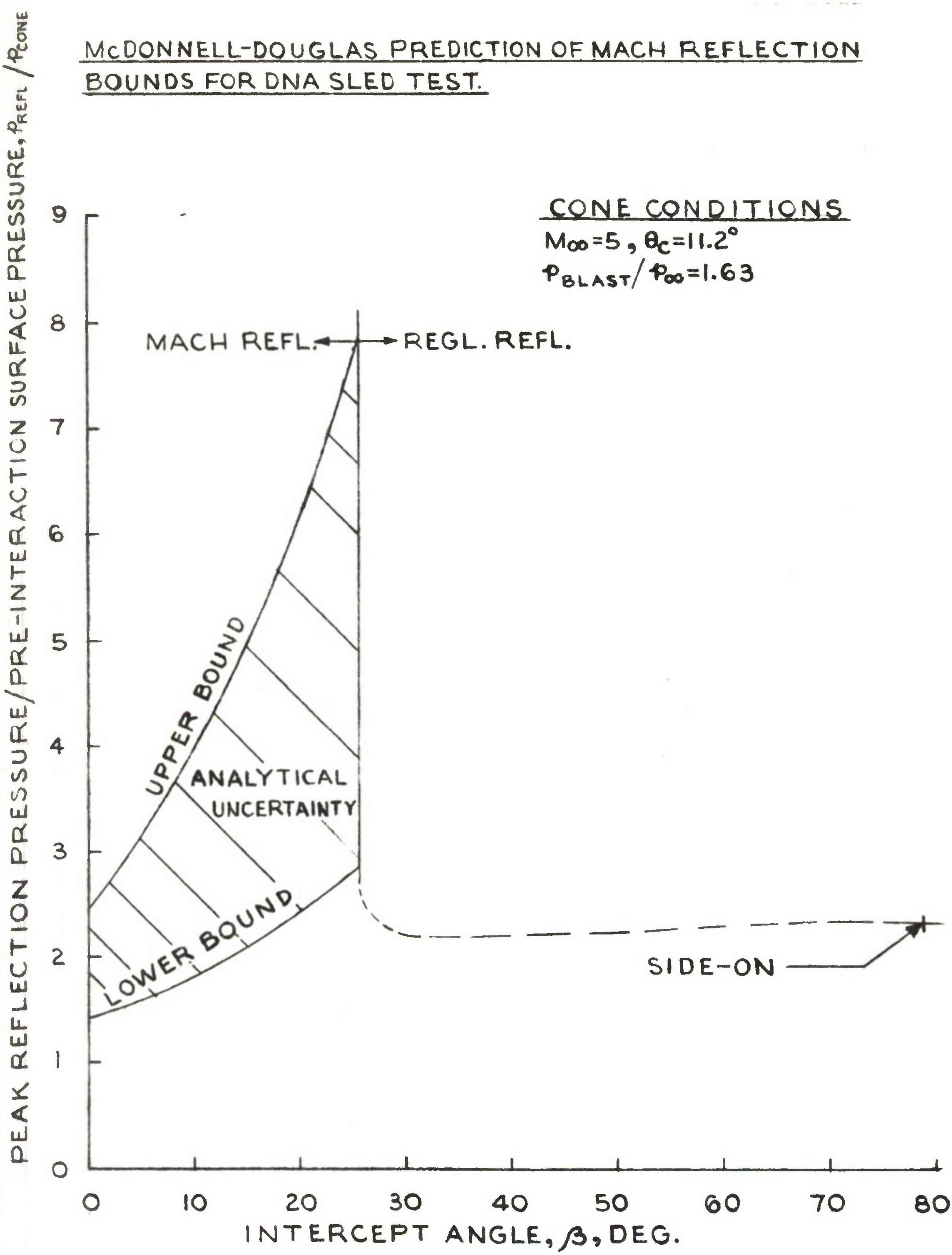


FIG. 3.

COMPARISON OF CONE AND WEDGE SOLUTIONS

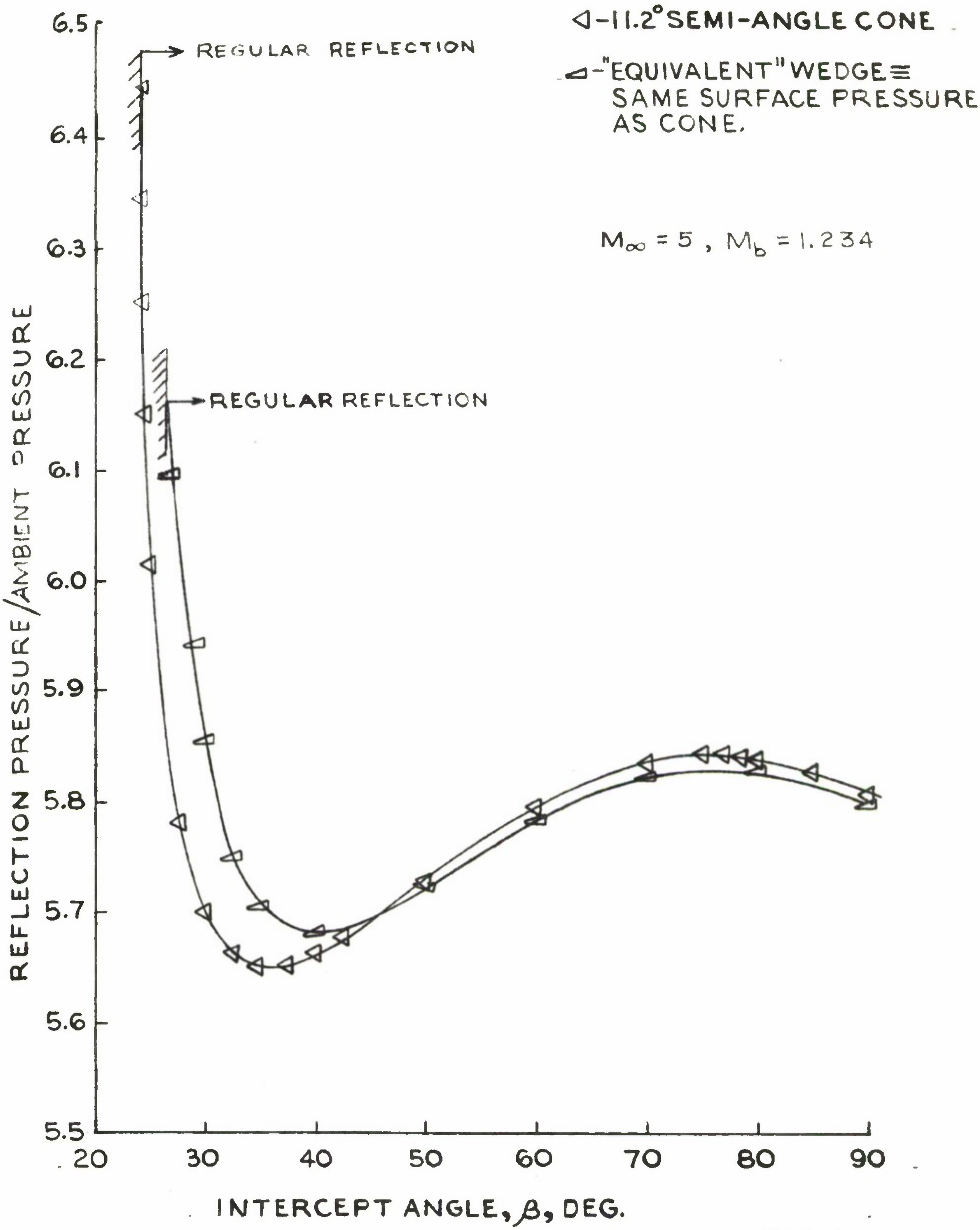


FIG.4.

COMPARISON OF WEDGE SHOCK-SHOCK METHODS

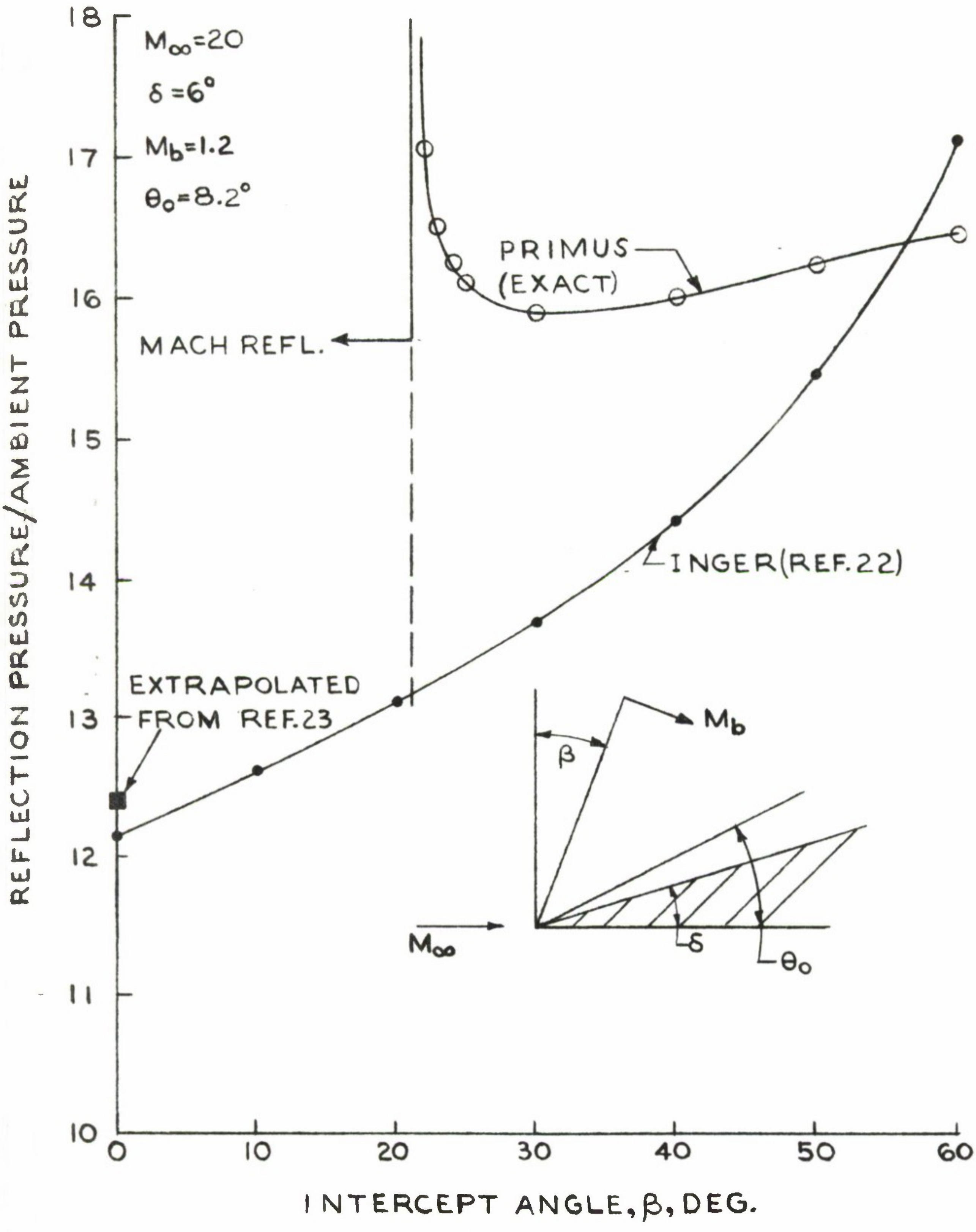


FIG. 5.

DNA SLED TEST 4B-B3-COMPARISON OF SEVERAL THEORIES AND EXPERIMENT.

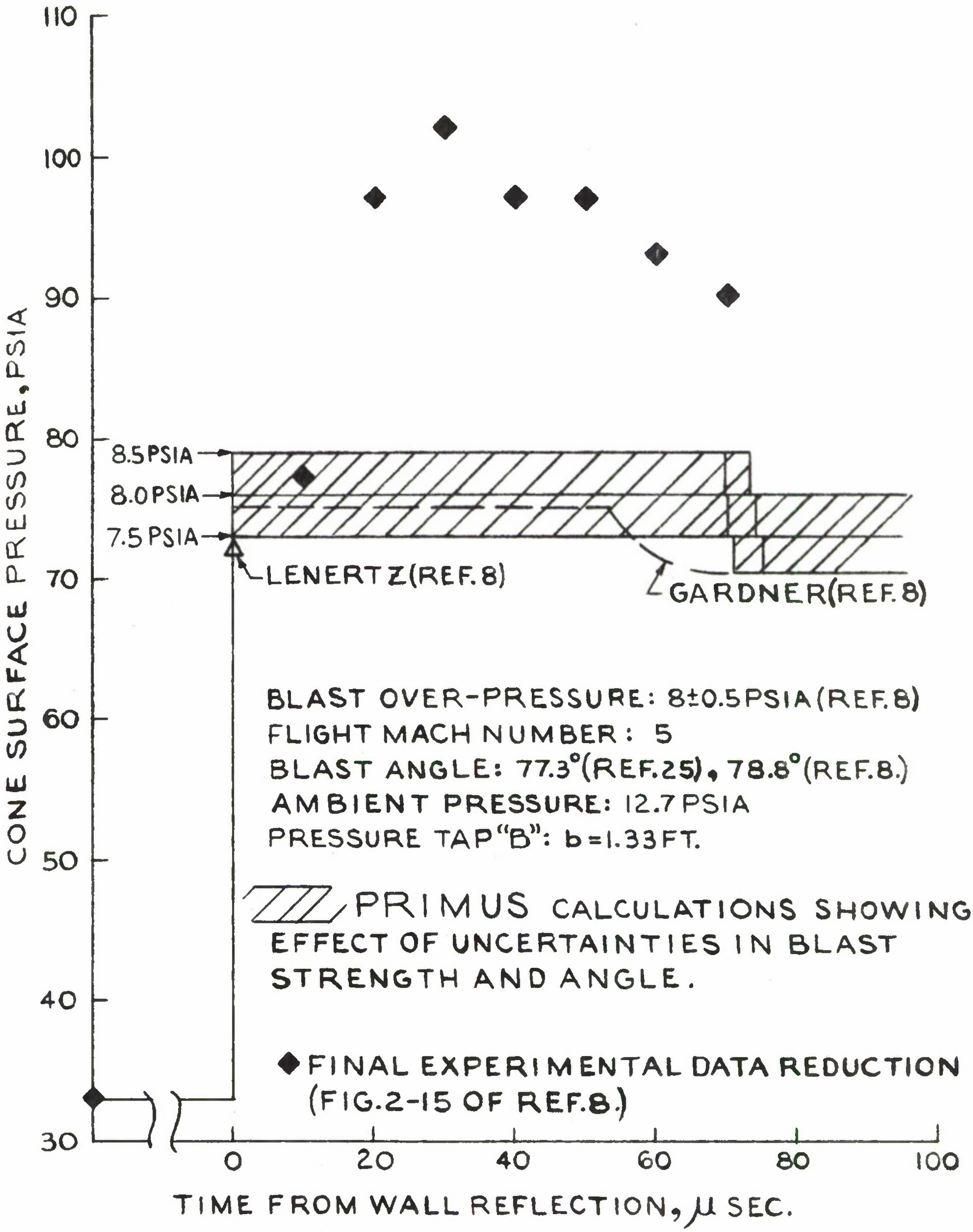


FIG. 6

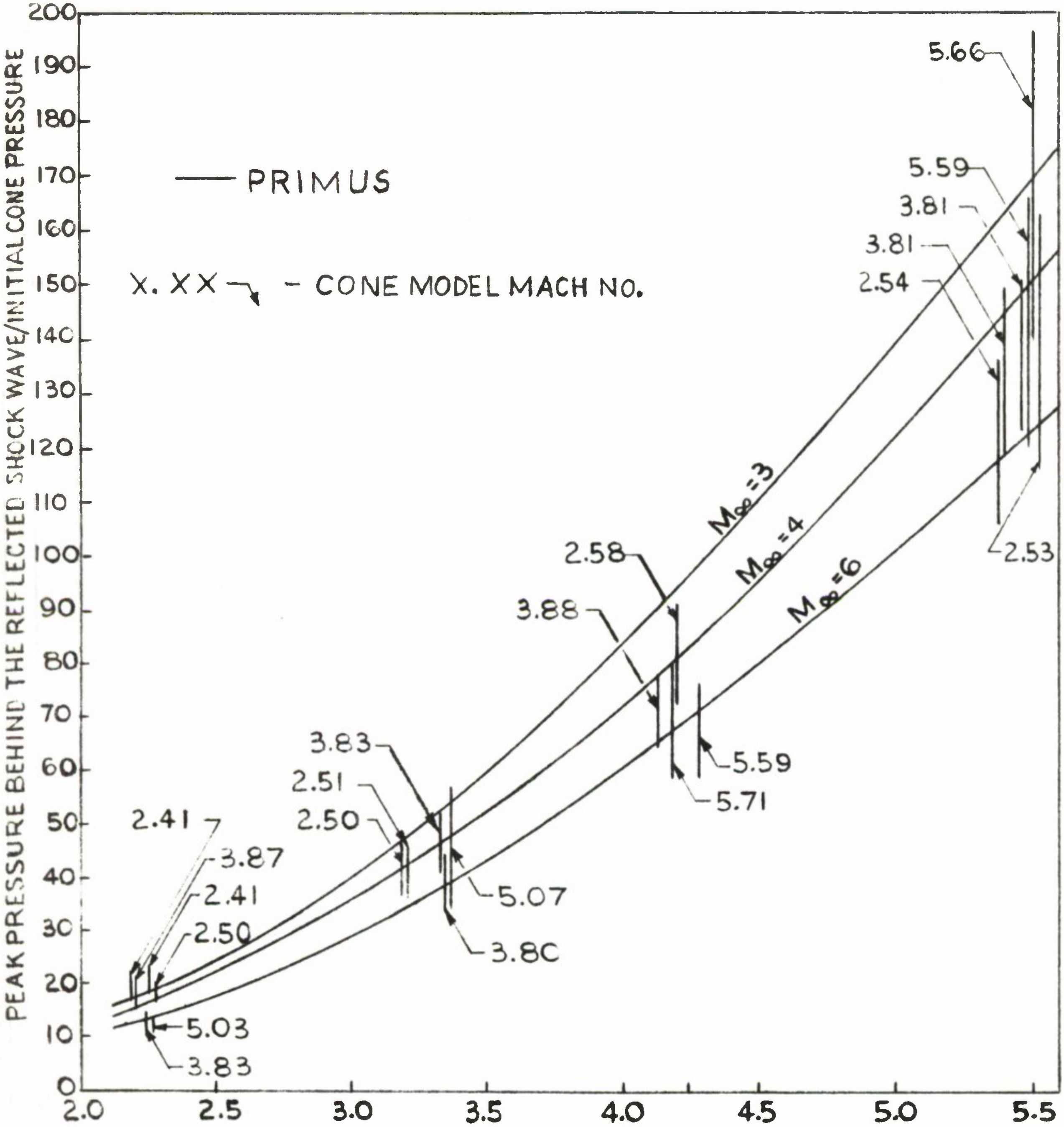


FIG. 7 RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. THE SHOCK WAVE MACH NUMBER – PRIMUS AND EXPERIMENT, 9° CONE MODELS

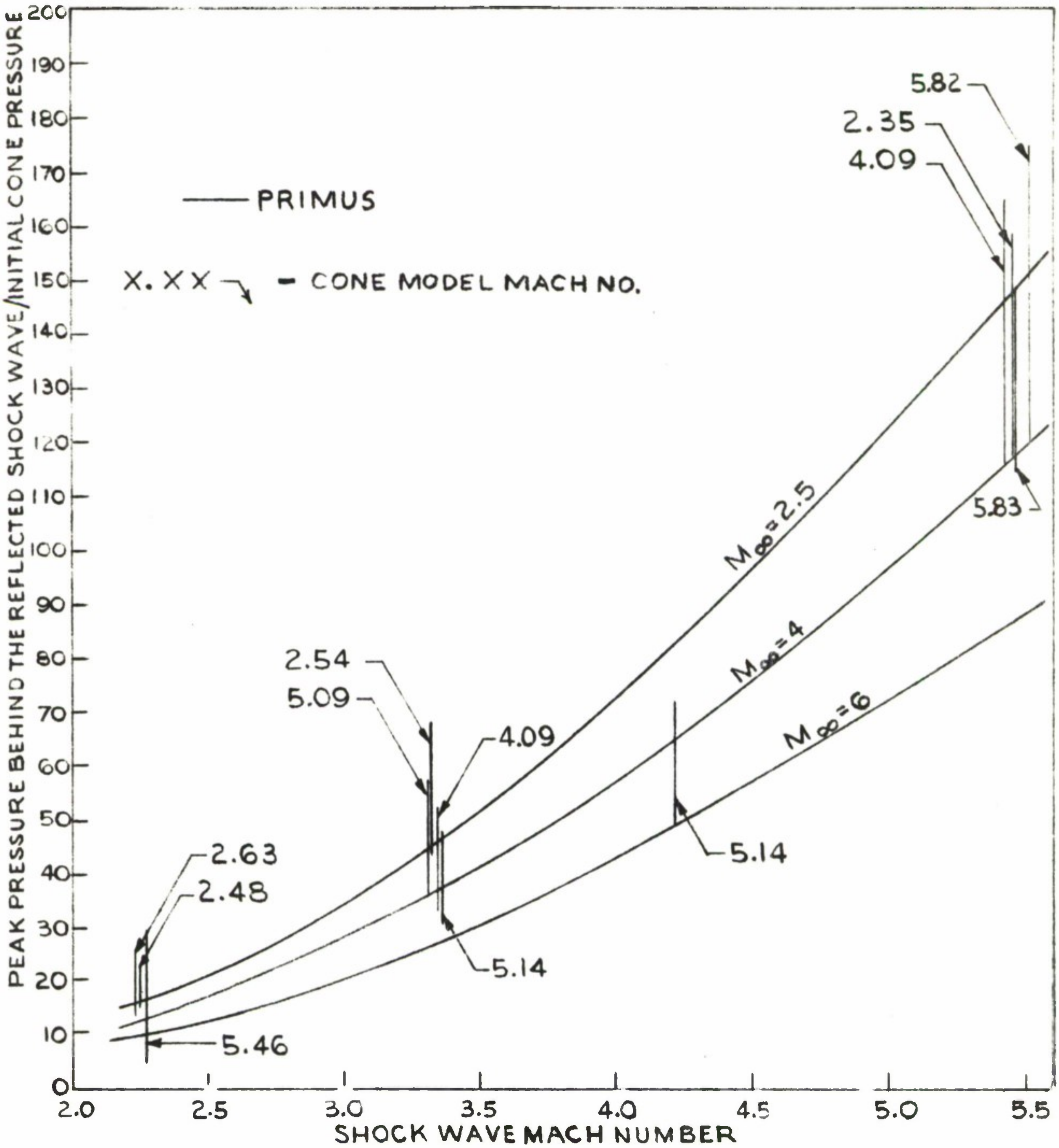


FIG. 8 RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. THE SHOCK WAVE MACH NUMBER - PRIMUS AND EXPERIMENT, 15° CONES

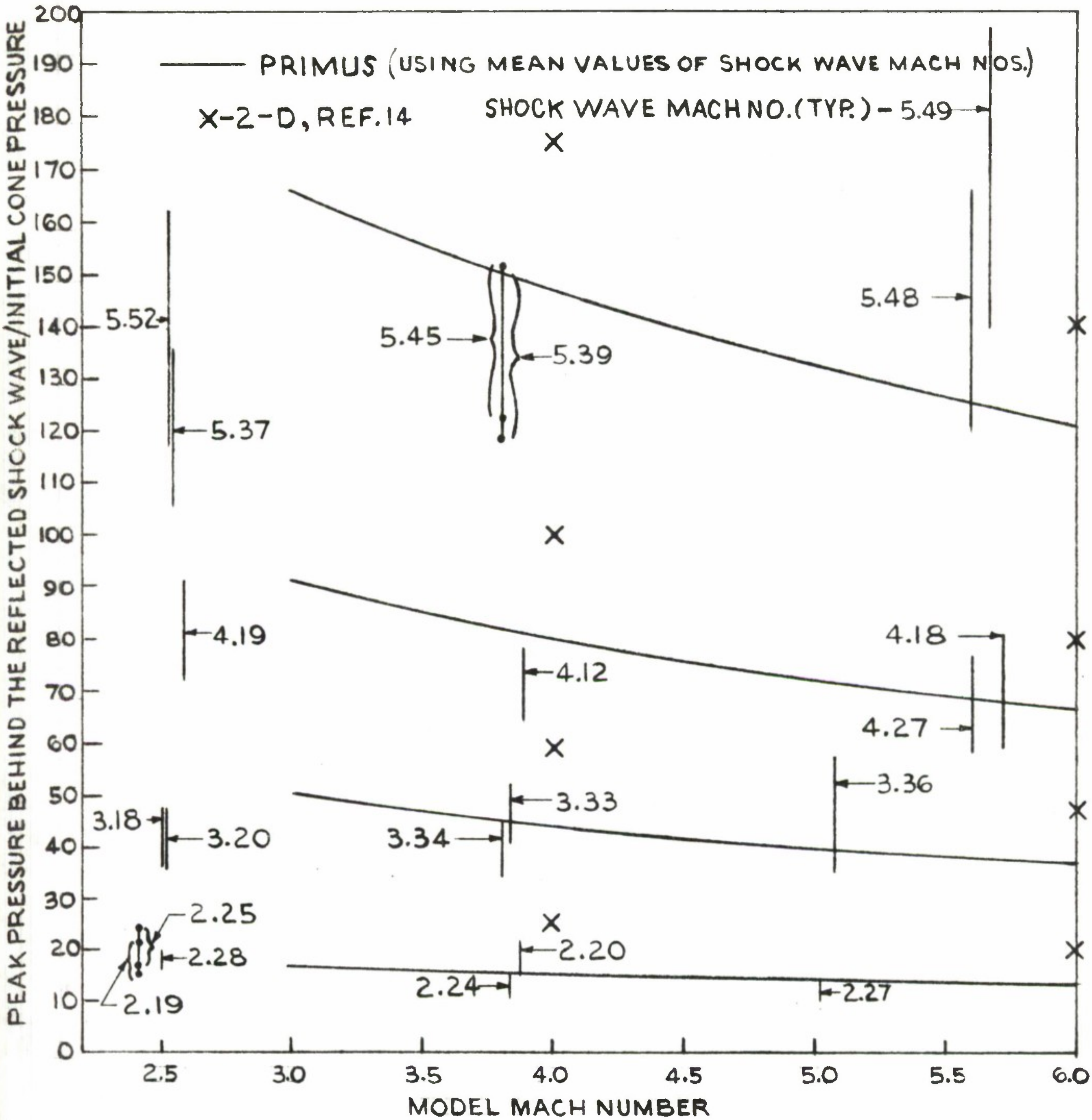


FIG. 9 RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. MODEL MACH NUMBER- PRIMUS, NOL, & EXPERIMENT, 9° CONE MODELS

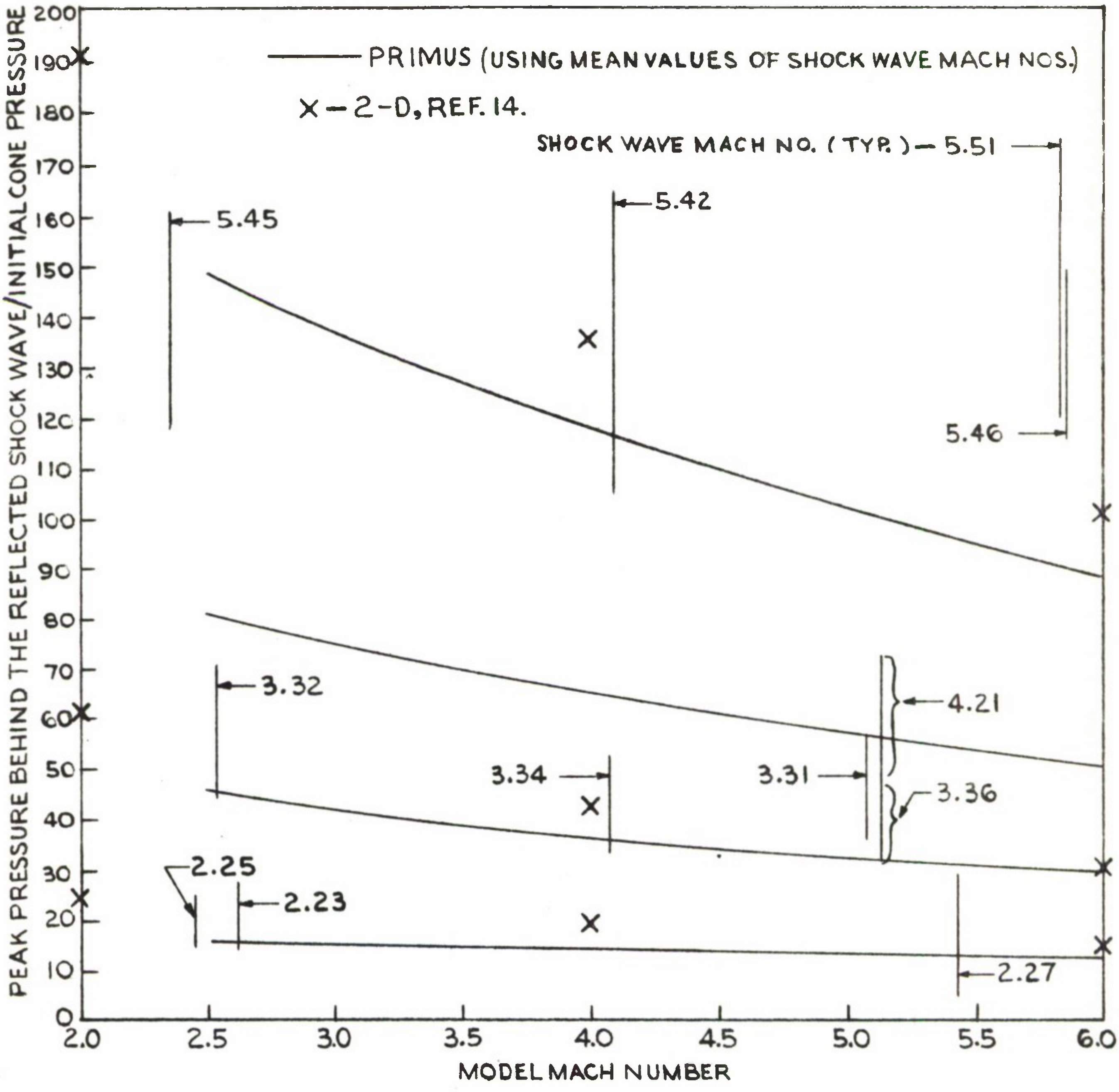


FIG. 10. RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. MODEL MACH NUMBER – PRIMUS, NOL, & EXPERIMENT, 15° CONE MODELS

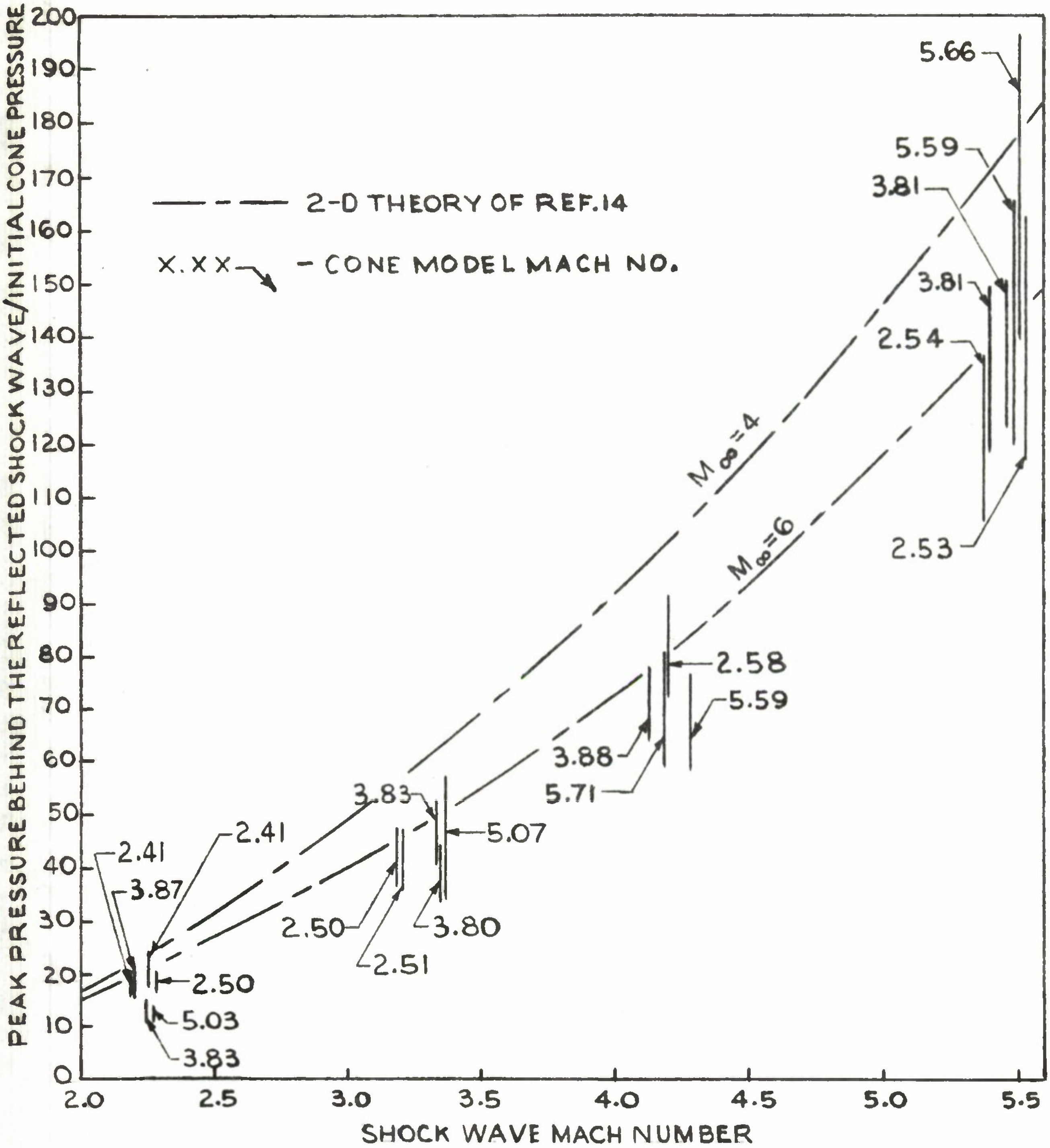


FIG.11 RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. THE SHOCK WAVE MACH NUMBER - THEORY AND EXPERIMENT, 9° CONE MODELS

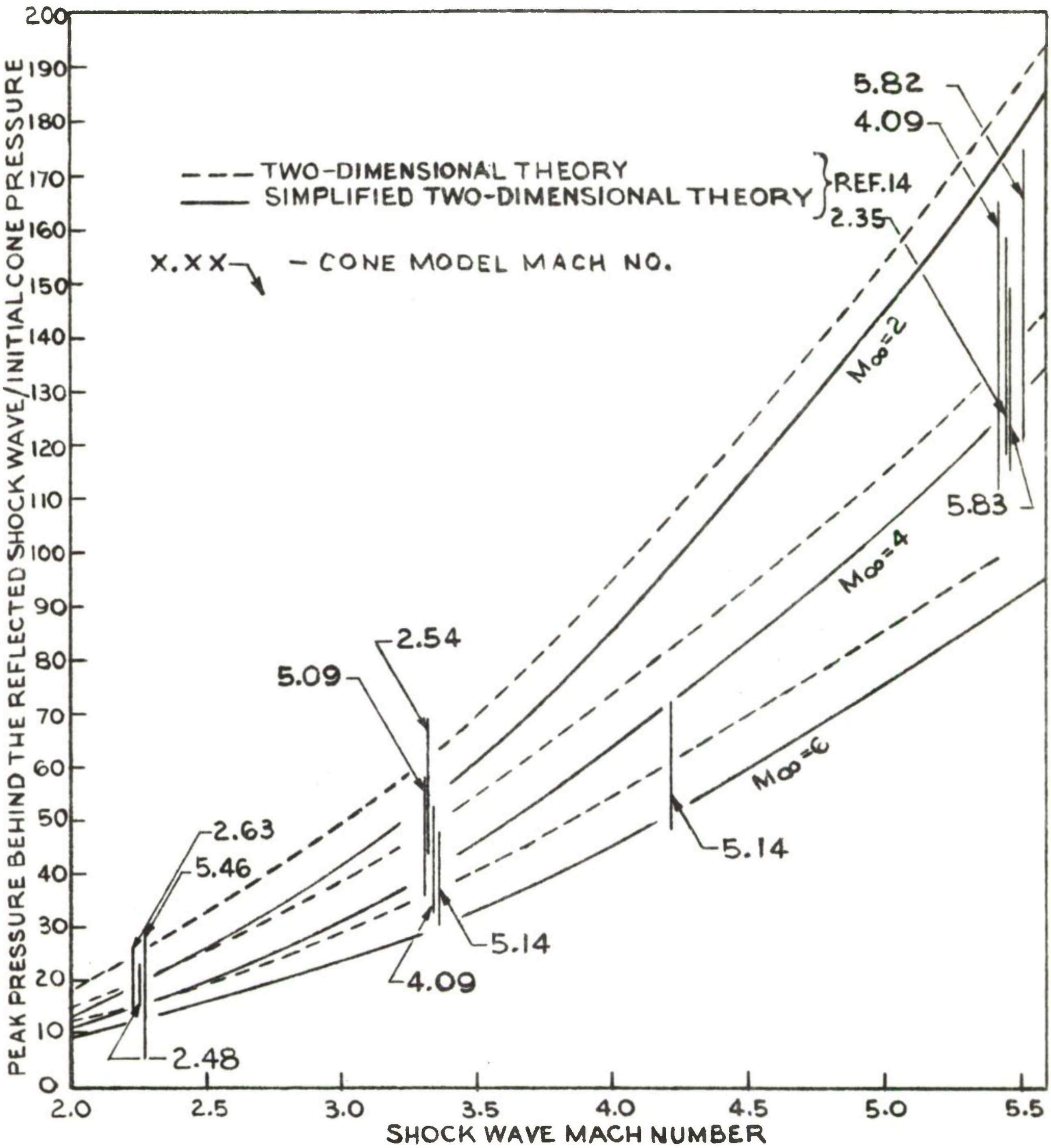


FIG.12 RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS.THE SHOCK WAVE MACH NUMBER—THEORY AND EXPERIMENT, 15° CONE MODELS

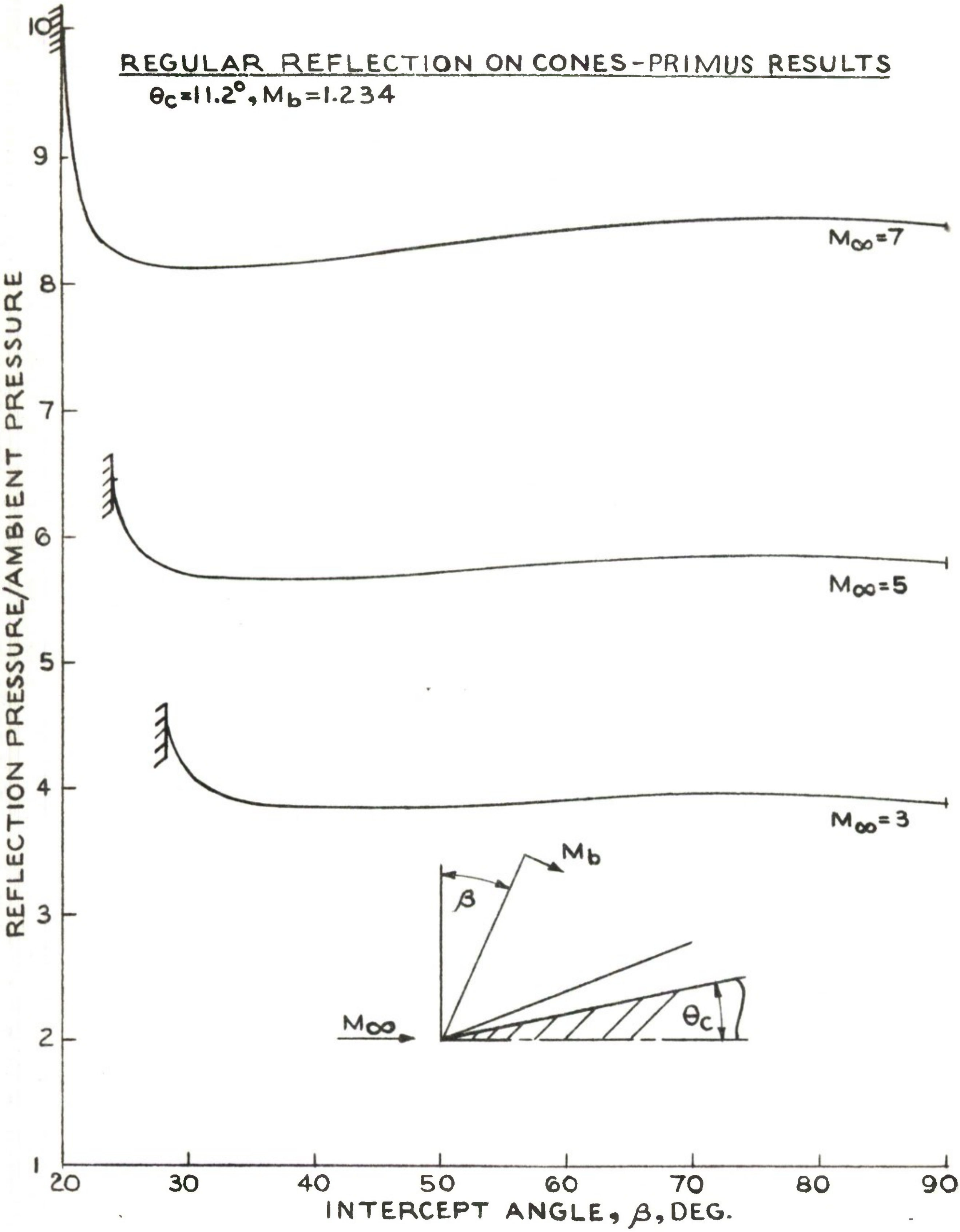

REGULAR REFLECTION ON CONES-PRIMUS RESULTS
$\theta_c = 11.2°, M_b = 1.234$
REFLECTION PRESSURE/AMBIENT PRESSURE
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
INTERCEPT ANGLE, β, DEG.
$M_\infty = 7$
$M_\infty = 5$
$M_\infty = 3$
M_b
β
M_∞
θ_c

FIG. 13.

COMPARISON OF MAXIMUM AND SIDE-ON PRESSURES FOR REGULAR REFLECTION

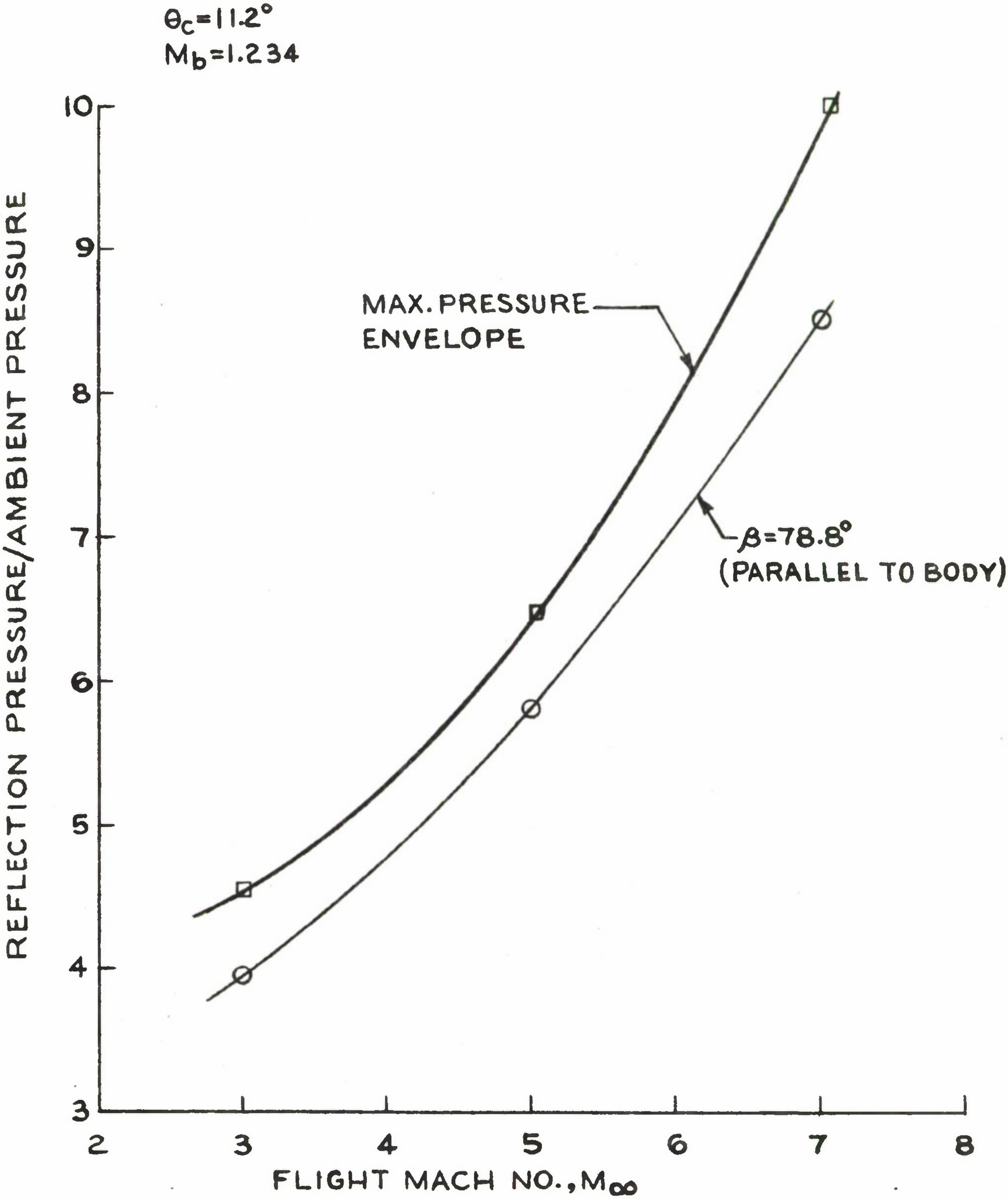


FIG.14.

COMPARISON OF TWO WEAK BLAST CASES FOR VALIDITY OF HYPERSONIC SIMILITUDE

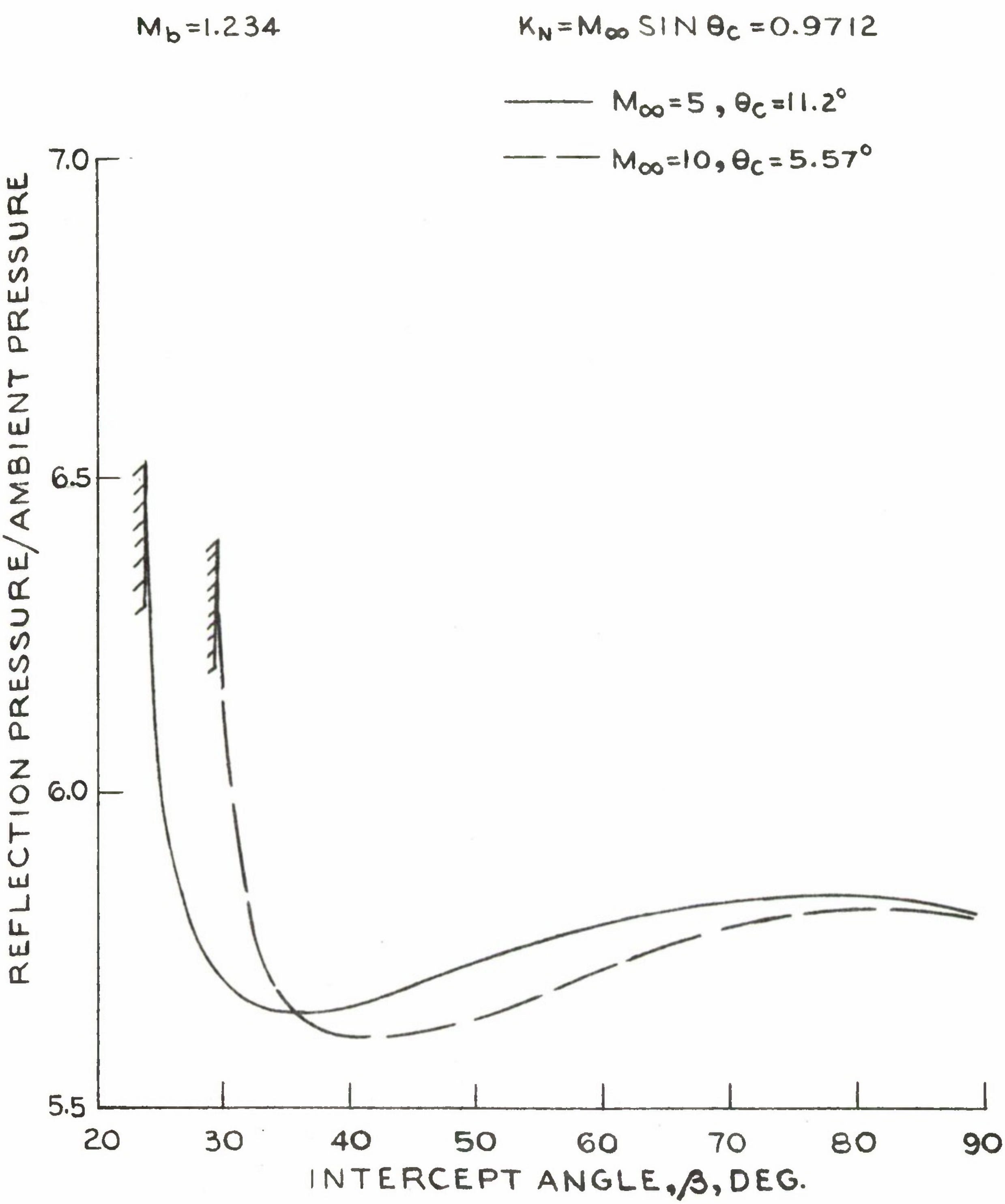


FIG. 15.

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13. ABSTRACT

The shock-shock interaction problem for weak incident waves impinging on a supersonic cone has been examined. The purpose of this study was to establish methods for predicting surface pressures since existing methods have been found inadequate for practical problems with weak blast waves. It is shown in this study that one-dimensional theory, which works well for strong blast waves, fails when the components normal to the surface of the flight velocity and of the blast particle velocity become comparable. As a consequence, an axisymmentric two-dimensional solution method was developed using a "primary wave" approximation. This approach has been automated in the PRIMUS computer code. The predictions from the code have been checked against experiment and other theory. The comparisons are presented and the agreement is quite good. The code was also used to predict the cone pressures for DNA Sled Test experiments. The results are presented and compared with the experimental results and other theoretical predictions.

This study established that for weak blast waves the maximum pressure for regular reflection occurs at the Mach reflection limit, not at side-on intercept. The question of whether reflection pressures are even higher on the Mach reflection side of the boundary was examined, but existing

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Shock - shock interaction						
Weak Waves						
Regular reflection						
Finite - difference methods						
Primary wave methods						
One - dimensional unsteady flow						
Two - dimensional unsteady flow						
Conical flow						
Wedge flow						
Shock Waves						
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